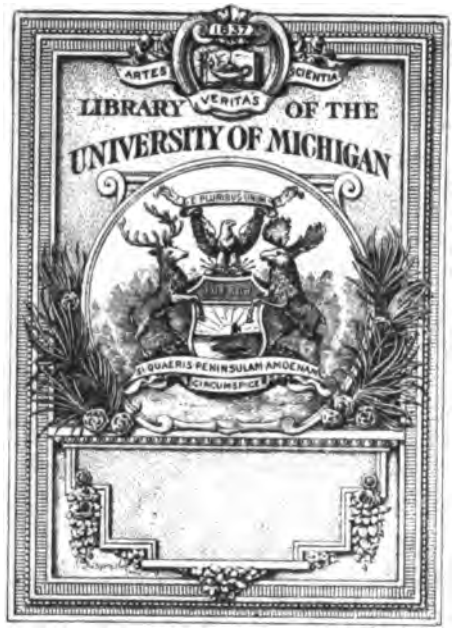
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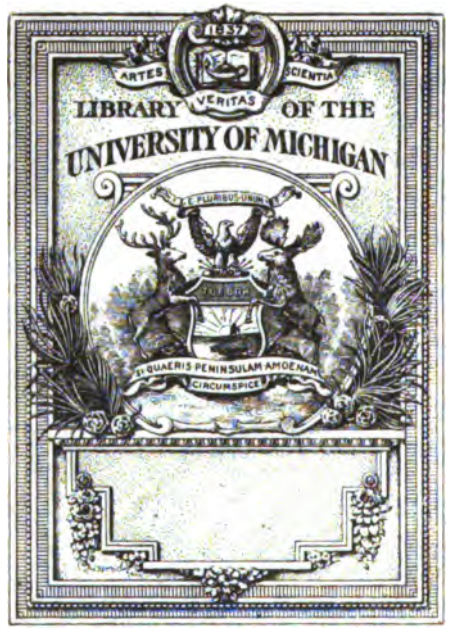
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[*Frontispiece.*

Sir William Chandler Roberts-Austen. K.C.B., D.C.L., D.Sc., A.R.S.M., F.R.S.

Photo. by Sir Benjamin Stone taken at the Royal Mint.

ROBERTS-AUSTEN

A RECORD OF HIS WORK.

BEING A SELECTION OF THE ADDRESSES AND METALLURGICAL PAPERS, TOGETHER WITH AN ACCOUNT OF THE RESEARCHES

OF

SIR WILLIAM CHANDLER ROBERTS-AUSTEN,
K.C.B., D.C.L., D.Sc., A.R.S.M., F.R.S.,

LATE CHEMIST AND ASSAYER OF THE ROYAL MINT; PROFESSOR OF METALLURGY IN THE ROYAL SCHOOL OF MINES HONORARY MEMBER OF THE INSTITUTIONS OF CIVIL ENGINEERS, MECHANICAL ENGINEERS, MINING AND METALLURGY, OF THE AMERICAN INSTITUTE OF MINING ENGINEERS, AND OF THE SOCIÉTÉ DES INGENIEURS CIVILES DE FRANCE; CHEVALIER OF THE LEGION OF HONOUR; PAST PRESIDENT OF THE IRON AND STEEL INSTITUTE; AUTHOR OF "AN INTRODUCTION TO THE STUDY OF METALLURGY," AND EDITOR OF GRIFFIN'S METALLURGICAL SERIES.

Memorial Volume

WITH PORTRAIT AND PLATES.

COMPILED AND EDITED BY

SYDNEY W. SMITH, B.Sc.(LOND.), A.R.S.M.,

ASSISTANT ASSAYER AT THE ROYAL MINT.

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1914.

constant inspiration to those who worked under him. These Addresses reveal how very much "worth while" he found metallurgy to be. In the care with which facts of interest and importance were garnered from all sources, they show the enthusiasm with which he sought to open out ways for the escape of what he felt to be "imprisoned splendour." The number and variety of the foot-notes and cross-references indicate his passion for exactness in detail, while his taste and literary skill are shown in the careful choice of suitable language in which to present his work.

To students not less than to others, these Addresses should be of value by reason of their clear and arresting statements of fundamental principles —principles with which each generation of students must become familiar before passing on to more specialised work.

An acquaintance thus gained with the work and aims of Roberts-Austen may help the student to approach the study of metallurgy with stronger convictions of its worthiness as a subject for the application of his fullest energies.

To the rapidly widening circle of men who have been trained on the lines which he did so much to define, a due appreciation of the nature and scope of his activities will perhaps be easier, by reason of their training, than it was even to his contemporaries.

While pursuing his researches under laboratory conditions, Roberts-Austen ever kept in touch and sympathy with the point of view of the practical metallurgist engaged in economically extracting and efficiently preparing for use those metals with which his own enquiries were concerned.

By his remarkable gift of exposition, inspired by the zeal of an enthusiast, he enlisted the interest and support of those who were best able to further the work of progress. His teachings were not only directed to the student, but he took every opportunity of bringing home to metallurgists and engineers the necessity for closer attention to the thermal and molecular changes in masses of metal in preparation for structural purposes. His views were often enforced by the repetition of what might appear to be commonplace experiments, but such experiments were recognised by him to be of an importance too rarely realised. To his perseverance in this pioneer work is due, in no small measure, the access of the true scientific spirit to channels hitherto choked by empiricism.

The quotations with which he prefaced his "Introduction" may be taken as the deliberately chosen expression of his own personal endeavour.

> "I rather open, than discover things."
>
> *Montaigne's Essays* (1580).

> "To know
> Rather consists in opening out a way
> Whence the imprisoned splendour may escape,
> Than in effecting entry for a light
> Supposed to be without."
>
> *Browning's "Paracelsus"* (1835).

Roberts-Austen's many activities possess a significance which may be viewed apart from the work which he actually accomplished. It is possible to see in them some manifestation of that indefinable spirit which prompts research and imparts to others the spirit of emulation, making the seeming commonplace worth while.

In considering what is likely to be effectual in leading men to undertake research work, he saw that little can be expected from precept, whereas much may be accomplished by example. It is hoped that the publication of this record of Roberts-Austen's work may be helpful in that direction, as a personal knowledge of him has been to so many who are now among the foremost workers in metallurgical research throughout this country. It is hoped, too, that the place which he filled, during a life untiringly devoted to the advancement of metallurgy, may now be more fully realised.

S. W S.

February, 1914.

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ROBERTS-AUSTEN.

I.

OUTLINE OF ROBERTS-AUSTEN'S CAREER.

WILLIAM CHANDLER ROBERTS was born in 1843. His father, George Roberts, was of Welsh extraction. His mother belonged to the Kentish families of Austen and Chandler.

In 1885 he became the heir of his uncle, the late Major Austen, J.P., of Haffenden and Camborne, in Kent, and was granted Royal Licence to add the name of Austen. To avoid confusion, the name Roberts-Austen, by which he was known in later years, has been adopted throughout, although his earlier work was published under the name of Roberts. His ancestry possesses many points of interest. Particular mention may be made of one which connects him with Isaac Casaubon, of Geneva, who, coming to this country in the seventeenth century at the invitation of James I., profoundly influenced English thought. By reviving at Oxford the study of Aristotle, he prepared the way for the advance of experimental science in the older universities. His son, Merick Casaubon, the first translator of Marcus Aurelius, settled in Canterbury, and became a Prebendary of the Cathedral. He married into a Kentish family, and from this union Roberts-Austen was able to trace his descent.

The following are the chief events in his career arranged in chronological sequence :—

1861. Entered the Royal School of Mines at Jermyn Street.
1865. Completed the course and obtained the Associateship in Metallurgy, and shortly afterwards became Private Assistant to Thomas Graham at the Royal Mint.
1866. Elected a Fellow of the Chemical Society.
1870. Appointed "Chemist of the Mint," and in the same year became also the "Second Resident Assayer."
1870. Visit to Foreign Mints.
1875. Elected a Fellow of the Royal Society.
1879-81. Served on the Council of the Chemical Society.
1880. Succeeded Dr. Percy in the Chair of Metallurgy at the Royal School of Mines.
1881. Elected a Member of the Iron and Steel Institute.
1882. Entrusted with all the Assay work at the Royal Mint, with the title of "Chemist and Assayer of the Mint."
1884. Visit to Mints of the United States.
1885. Member of the Executive Council of the Inventions Exhibition.
1889. Appointed to the Alloys Research Committee of the Institution of Mechanical Engineers.
1889. Served on the British Executive Council of the Paris Exhibition.
Vice-President of the International Mining and Metallurgical Congress in Paris.
Received the Cross of Chevalier of the Legion of Honour.

1890. Appointed to a Companionship of the Order of the Bath.
1890-2. Member of Council of the Royal Society.
1890. Member of Council of the Iron and Steel Institute.
1891. Publication of the First Report of the Alloys Research Committee, subsequent Reports appearing in 1893, 1895, 1897, and 1899.
Publication of the First Edition of the Introduction to the Study of Metallurgy, subsequent editions appearing in 1893, 1894, 1897, and 1902.
1893. Served on the British Executive Council of the Chicago Exhibition.
Elected a Member of the Athenæum Club under Rule II. for distinguished work.
1895-8. Vice-President of the Chemical Society.
1896. Appointed to a Board of Trade Committee on the "Wear of Steel Rails."
1897. Served on the Treasury Committee entrusted with the establishment of the National Physical Laboratory.
Vice-President of the Iron and Steel Institute.
Elected Honorary Member of the Institution of Mechanical Engineers, of the Institution of Mining and Metallurgy, and of the American Institution of Mining Engineers.
1898. The degree of D.C.L. conferred by the University of Durham.
The degree of D.Sc. conferred by the Victoria University.
Became one of the General Secretaries of the British Association, which office he continued to fill until the time of his death.
1899. Promoted to be a Knight Commander of the Order of the Bath.
1899-1901. President of the Iron and Steel Institute.
1899-1902. Member of a War Office and Admiralty Committee on Explosives and Ordnance.
1901. Elected Honorary Member of the Institution of Civil Engineers and of the Societé des Ingenieurs Civiles de France.
1902. Acting-Deputy Master of the Mint from August until his death on November 22nd.

II.

HIS WORK AT THE ROYAL MINT.

Assistant to Graham—Official Appointments—Researches from 1870 to 1879; 1880 to 1890; 1891 to 1902—References in the Annual Mint Reports—Cantor Lectures on Alloys used for Coinage—"The Queen's Assay Master"—Tributes to Graham.

It is quite impossible to deal with Roberts-Austen's work at the Mint as a matter apart from his many activities in all directions. It was probably from the fortunate circumstances of his early association with Thomas Graham (then Master of the Mint) that he derived the inspiration which in later years carried him to the foremost rank of metallurgists.

Graham's whole life had been devoted to the study of the conditions and motions of molecules and atoms. It may be claimed for Roberts-Austen that he carried the spirit of this work into the domain of metallurgy, and in so doing helped to create an entirely new school of metallurgists—a school of men whose equipment is no longer limited to a knowledge of chemical reactions and chemical equilibrium, but who have linked to this knowledge considerations derived from various branches of physics and mathematics.

Some of the earlier work in which Roberts-Austen was associated with Graham typifies very clearly this transition from physical chemistry to physical metallurgy. This earlier work, and in particular the now classical study of the peculiar relations subsisting between palladium and hydrogen, had for its object the elucidation of the conditions under which gases are occluded by metals.

Roberts-Austen's work at the Mint touches the whole of his work as an investigator, for, although the Royal School of Mines claimed his time and energy as a lecturer to students, by far the greater part of his original work was done under the more sequestered conditions of his Laboratory at the Mint. Here he created an atmosphere suited to his own peculiar methods of work, and, assisted by men whom he had brought from the School of Mines and trained in these methods, he was able to establish a continuity of work with freedom from the distracting demands of students, anxious for the most part to get through their course, with little time for research work, and, perhaps, but little sympathy with it.

It is quite certain that Roberts-Austen formed a great attachment for the Mint, and the many years during which he lived and worked there were undoubtedly happy years. He fully realised the dignity and trust of the office which he filled, and although the work and responsibility which it involved would sufficiently occupy the energies of most men, yet such was his activity that this work, although in no wise neglected, really appeared to be regarded by him as incidental to the main purpose of his life—the progress of his researches.

Much as he loved the home which in later years he had made in Surrey, it was in the quiet evenings at the Mint, when the noise of traffic on Tower Hill was hushed, that he evolved some of his brightest plans and most daring speculations. Something, too, of the antiquity and traditions of his office appealed to his nature in a special way, lending, as it were, an appropriate setting to his work, and satisfying those elements of his æsthetic nature which, in other surroundings, might possibly have found less opportunity of expression.

To the Mint came people of all nationalities, to whom he ever extended a cordial welcome, and with whom an exchange of ideas left an afterglow of stimulus to the work in hand.

It is possible to trace in the earlier work at the Mint the genesis and growth of work which in the fulness of his career made him famous in wider fields, and established his authority in matters far removed from the relatively limited operations of minting. Thus, his devotion to problems involving the accurate measurement of temperature naturally arose from his daily experience of the delicate processes of assaying, in which the success and value of the operations depend upon a proper appreciation of the importance of slight variations at high temperatures.

His particular distinction in the field of iron and steel had its origin in his investigations of the properties and behaviour of die steel.

The need for producing suitable "patinas" on the surfaces of metals which should be both pleasing and lasting, led to his very notable achievements in art metal work. His artistic sense of what was appropriate did much to ensure the beauty and finish of the medals which from time to time the Mint was called upon to produce.

Although in later years the Government absorbed most of his time and energies on Departmental Committees—of the Board of Trade, the War Office, and as Professor of Metallurgy at the Royal School of Mines—yet he still found time to carry on work bearing directly on the metallurgy of gold and silver and the operations of coinage. Meanwhile he never released himself from his share in the every-day responsibilities of the routine work of assaying, until on the death of the Deputy-Master (Sir Horace Seymour) in 1902, he was called upon to add the duties of that office to those of his own. His health was then failing, and his death occurred a few months later.

In the following pages an attempt will be made to review in some detail the more prominent features of that portion of his work which had a special bearing on the operations of coinage and the general work of the Mint. Before doing so, however, it will be interesting to trace the origin of Roberts-Austen's first official appointment as affording a means of estimating the extent to which he may be said to have inherited from Graham the traditions of scientific research, which had for so long been associated with the office which Graham filled.

Officially appointed at the Royal Mint.—The precise status of the position which Roberts-Austen was called upon to fill on the death of Graham is of interest. As Master of the Mint, Graham was the successor of eminent men, distinguished for their scientific work. In fact, this post was perhaps one of the first, and moreover one of the few, in which the Government gave direct recognition to scientific distinction.

At the time of Graham's death, however, the Lords Commissioners of

the Treasury had under consideration the re-organisation of all the Departments of the Mint, and one of the changes which were effected was in the nature of the office of Master of the Mint. In a Treasury Minute, dated 7th of January, 1870 (four months after Graham's death), reference was made to the proposed changes, as follows :—

"My Lords have under consideration the arrangements necessitated by the death of Professor Graham, Master of the Mint, and proceed to state the conclusion at which they have arrived with reference to the future administration of that branch of the public service.

"My Lords propose that the actual administration of the Department shall in future be entrusted to the 'Deputy Master and Comptroller,' and that the office and title of 'Master of the Mint' shall, however, be still retained, and shall be held by the Chancellor of the Exchequer for the time being, without salary."

A later portion of the same Minute foreshadowed possible changes in the arrangements for conducting the Assay Work in the Mint, and it is in this portion of the Minute that we see how it was made possible for Roberts-Austen to be retained at the Mint in an official capacity, his position under Graham having been that of a private assistant working in his laboratory, and in no way associated with the assay work which was carried on under distinct control. Following the announcement that, for the present, there would be no alterations in the Assay Department, the Minute says :—

"My Lords take this opportunity, however, of recording their opinion that whenever the offices of non-resident assayers shall become vacant, an improvement may be effected in the system of assaying for the Mint by substituting for the so-called 'Out-door Assayers,' who are paid by fees, a second salaried Resident Assayer, who would assay the bars when standardised and the coined pieces, as is now done by the Non-Resident Assayers.

"Meanwhile cases will occur when the assistance of a practical Chemist within the Mint would be desirable. My Lords propose to avail themselves of the opportunity of securing the services of Mr. W. Chandler Roberts, who for several years has acted as Private Assistant to the late Master of the Mint, is fully conversant with the operations of the Mint, and of whose experience and special aptitude my Lords have received very satisfactory assurances. Mr. Roberts will, therefore, hold the office of Chemist to the Mint. He will continue to occupy the Second (No. 2) Assay Office, hitherto used by Professor Graham, and upon the termination of the arrangement with the Non-Resident Assayers, my Lords will be prepared to give a favourable consideration to his claims to be appointed Second Resident Assayer."

The opportunity for giving "a favourable consideration to his claims" arose very shortly afterwards. The question of the abolition of the offices of Non-Resident or "Outside" Assayers was re-opened before the end of the year, when one of those offices became vacant by the death of Dr. W. A. Miller, F.R.S., Professor of Chemistry at King's College. The result was that the changes which had been foreshadowed were actually effected, and the Assay Department was re-organised on December 3rd, 1870.

Robert-Austen was given the appointment of Assayer, with charge of the Second (No. 2) Assay Office (as Graham's laboratory was then called), and the duty of assaying all bars which had been standardised for coinage and the finished coined pieces, the fine gold and fine silver imported into the Mint for coinage being still assayed by the Resident Assayer, Mr. Ridsdale.

This arrangement was in reality a return to an earlier practice which had been changed in 1851, but with this notable difference, that Roberts-Austen brought to his new office the duties and traditions of the Scientific Officer of the Mint, which had hitherto formed part of the office of the Master of the Mint.

Thus for many years the assay work of the Mint was carried on by the two offices exercising separate control—one over the bullion imported into the Mint and the other over the coin issued to the country.

This arrangement continued for eleven years, until (in 1882) a further change was effected, with the result that the two Assay Offices were merged into one, and the sole responsibility for the assay work devolved upon Roberts-Austen, whose title now became "Chemist and Assayer of the Mint."

A review of the considerations which led to this change may be gathered from an extract from the 12th Report of the Deputy-Master of the Mint (1881):—

"Since the beginning of the present year their Lordships have been pleased to sanction an important change in the Assay Department. The establishment of the Assay Department was fixed in 1871. In that year the appointments of the Non-Resident Assayers were discontinued, and a second Assayer was added to the staff of the Mint to perform the duties assigned to them. This change was only a return to the system in force before 1851.

"Under the arrangements which prevailed up to that time the operations of coining were performed by a Company of Moneyers under contract with the Crown, and it was necessary that, in addition to the Assayer, whose duty it was to protect the interests of the Master of the Mint, and who was styled the 'Master's Assay Master,' there should be an Officer independent of the Master of the Mint, styled 'Queen's Assay Master,' who should be responsible to the Sovereign for the standard fineness of the coin. Since 1851, however, when the contract system was abolished, and the Master of the Mint became solely responsible for the correctness of the coinage, the same reasons have not existed for maintaining two separate Assay Offices. The Master of the Mint can no longer be brought into conflict with the interests of a body of contractors, and his responsibility to the public is amply secured by the Trial of the Pyx, which, under the Coinage Act of 1870, must be held once every year, and constitutes a very severe test of the integrity of the gold and silver coinages.

"The nature of the work performed in each Assay Office may be briefly stated.

"In Office No. 1, corresponding to that formerly conducted by the Master's Assayer, all bullion brought to the Mint for coinage has been assayed, the results serving as a check upon the 'trade' assay report which accompanies each ingot. The value at which the bullion will be received by the Mint is thus determined, and the Mint Assays also afford the basis for

calculating the amount of the alloying metal to be added to bring the bullion to the standard prescribed by law.

"In Office No. 2, corresponding to that formerly in charge of the 'Queen's Assay Master,' the bars into which the standard metal is cast by the Mint have been assayed, as have also samples of the coin struck from day to day. It is by means of this office, therefore, that the fineness of all coin issued has been verified and secured. In it the work has been nearly continuous, while in Office No. 1, which has only been employed during the time that importations of ingots have been actually in progress, it has necessarily been liable to periods of suspension. The experience of the past ten years has satisfied the Master of the Mint that the necessity for maintaining two separate Assay Offices no longer exists, and that no risk of error is created by entrusting all the assays to a single officer. There will still remain the check afforded by the 'trade' assay reports, and the work will not be more liable than heretofore to the risk of personal error on the part of a single Assayer, as the operations of which an assay consists will be performed, as heretofore, by several individuals, one officer being responsible for the method in which it is conducted.

"Under this arrangement the management of the Assay Department has devolved upon Mr. W. Chandler Roberts, F.R.S., Chemist of the Mint, the Assayer in charge of Office No. 2, and the two Assistant-Assayers, Messrs. F. W. Bayly and E. Rigg."

One of the results of the changes in the administration of the Mint (referred to on p. 5) was the inauguration of a series of Annual Reports on the work of the Mint made to the Treasury by the Deputy-Master for the use of the House of Commons.

Fortunately, this innovation coincides with the commencement of Roberts-Austen's official career, so that it is possible to follow the progress of his work from the Memoranda which he made each year for inclusion in these reports.

A complete bibliography of all references to his work which are contained in these Reports is given later, so that it will be unnecessary to give foot-note references in the course of the review, except in special cases.

WORK AT THE MINT, 1870-1879.

Shortly after his appointment, in 1870, as Chemist of the Mint, Roberts-Austen was directed to undertake an inspection of the
1870. European Mints, in company with the Deputy-Master (Sir Chas. Fremantle) and Mr. J. M. Napier, in order to ascertain what special arrangements in force abroad it might be well to adopt in this country. Thirteen mints were visited, including Madrid, Milan, Florence, Rome, Constantinople, Vienna, St. Petersburg, Stockholm, Copenhagen, Berlin, Utrecht, Brussels, and Paris.

In his report he made an exhaustive survey of the differences in practice observed, and added valuable comments showing the importance of the enquiry in having afforded more exact knowledge of the comparative merits and deficiencies of the Mint practice at that time.

Thus, at the very outset of his official career, he had the unique and valuable opportunity of acquainting himself with all the phases of minting carried on under widely varying conditions. It was, doubtless, during these visits that the foundations were laid of many of those associations with men of science on the Continent, which in later years developed into important relationships, having, in many cases, an international significance.

On entering upon his duties at the Mint, Roberts-Austen first directed his attention, quite naturally, to making sure of his position as the assayer responsible for the correct composition of the coin issued from the Mint. His careful review of the processes of assaying as he found them, which appears in the *First Mint Report*, shows that he devoted much time and thought to satisfying himself as to the possibilities and limitations of the methods then in use. The method of assaying gold, which has been practised for several hundred years without essential alteration, admitted of but few changes. Such changes as were effected were mainly in the direction of time-saving, so that the increasing demands of the work might be met without a large increase of staff. He pointed out that this so-called "parting assay" had been mentioned in a decree of King Philippe of Valois in the year 1343.

The method of silver assay by cupellation, which is also one of great antiquity, was at this time still retained at the Mint, although it had been superseded on the Continent for many years by the "volumetric method," originally devised by Gay-Lussac, and adopted at the Paris Mint in 1830.

Roberts-Austen at once introduced this newer method for the verification of the composition of the standard bars and coins, although the older method was still retained in the other Assay Office for several years. His confidence in the volumetric method had probably been firmly established by the opportunity which he had but recently had of conferring with Stas, who at that time was at the head of the Brussels Mint. Stas had introduced certain modifications in the original process which facilitated manipulation without changing any of the principles upon which it was based.

Having thus satisfied himself with regard to the foundations of the routine work, in which he never ceased to take a daily part, his mind was free to consider other problems.

The matters which first occupied his attention were naturally those most closely associated with the operations of coining.

At this time the difficulties caused by "brittle gold" (one of the eternal

problems of minting) were giving considerable trouble, and Roberts-Austen was directed to make an investigation into the causes of "brittleness," and the means by which this trouble might be remedied. He showed that the Chlorine Process of refining gold, which had then been recently devised by Mr. F. B. Miller, the Assayer at the Sydney Mint, could be employed in toughening the metal, and the important fact was demonstrated that this process can be conducted with but trifling loss of gold in the presence of the volatile chlorides of copper and other metals. Official recognition of the value of this work was given in a letter from the Treasury to the Deputy-Master (8th June, 1870).

The important work of preparing new Trial Plates was next entrusted to him by the Warden of the Standards. The Trial Plates were
1873. to constitute the legal standards of reference in checking the gold and silver coinages at the Annual Trials of the Pyx, and were also to be used throughout the Assay Offices of the United Kingdom in substitution for those then in use, which were known to diverge in composition from the standards prescribed by law. A detailed account of the precautions taken in the preparation of these plates is given in the Mint Report for 1873, and also of the methods adopted in the preparation of plates of fine gold and fine silver, which, on the recommendation of Roberts-Austen, were to be employed as supplementary to the Standard Plates.

The immediate outcome of this work, and of the difficulties which were encountered, was the inauguration of those important researches on
1874. the molecular arrangement of the constituents of alloys with which Roberts-Austen's name will always be associated, and which occupied his attention during the thirty years of activity which followed.

From the study of the problems connected with the liquation or segregation of the constituents of the alloys, of which these trial plates were
1875. composed, arose the necessity for accurate measurements of the temperatures of molten metals. The methods by which this could be accomplished were, at this time (1874), very laborious, and subject to many possible sources of error. The paper which Roberts-Austen contributed to the *Proceedings of the Royal Society* in 1875 (see pp. 256-265) indicates sufficiently the care and patience with which he applied calorimetric methods to the measurement of the temperatures of solidification of the alloys of silver and copper, combining his results in the form of a "freezing point curve" of the type which became so familiar to workers in later years. It was not until fifteen years later (1890) that he was able to adopt the more convenient thermo-couple methods of Le Chatelier, which he applied to the production of autographic records of the cooling and solidification of molten metals and alloys. This continued to be his chief implement of research until he adopted the methods of photomicrography in 1895, which he made complementary to it. From then on, until the time of his death, he continued to make effective use of these two implements of research in revealing the molecular changes taking place in solid and molten metals, and in demonstrating the reality of those changes by photographic means.

During these early years several researches were undertaken expressly for the purpose of ascertaining how far advances in science generally
1876. could be brought to bear on the operations of minting, and more particularly on those of assaying. Among these researches mention

should be made of extended experiments in quantitative spectrum analysis conducted in conjunction with Mr. (now Sir) Norman Lockyer.

As the result of these investigations, it was shown that it is possible to distinguish between alloys of gold and copper, which only differ in proportion by $\frac{1}{10,000}$ part, thus demonstrating at this early date that the spectroscope might be effectively employed for quantitative analysis. Although this work was not pursued further at the Mint, yet it marks the beginning of much important work in the same direction which has been subsequently carried on under the direction of Sir Norman Lockyer at South Kensington.

Researches were also conducted at this time on the molecular constitution of metals as indicated by the absorption spectra of their vapours at very high temperatures.

In 1876, experiments had been made by Dr. O. J. Broch, of Christiania, on the relations between the fineness of alloys of gold and copper

1877. and their densities. Roberts-Austen supplemented Broch's results by a more complete series of determinations. The research was extended by directing special attention to the effect of compression and annealing, and the results obtained provided physical constants in connection with gold, the determination of which had been long neglected.

In 1878 investigations were commenced with a view to extending the researches of Professor Graham on the "Transpiration of Liquids"

1878. to the passage of metals and alloys through capillary tubes while in the molten state. Roberts-Austen was thus actively engaged in carrying the spirit of Graham's work into the fields of metallurgy, and this research marks the beginning of work which subsequently became classical. The results of his work at this time formed the subject of two reports to the British Association.

Further attention was also given to alternative methods of ascertaining the fineness of gold alloys. In 1823 Becquerel had suggested that

1879. the standard fineness of an alloy might be indicated by the electromotive force developed when the alloy is placed in an exciting fluid together with an alloy of known composition. The subject had been partially investigated by Oersted in 1828, and, as its practical importance had been pointed out by Gay-Lussac in 1832, Roberts-Austen thought it desirable to make some experiments in order to ascertain how far the more delicate appliances then available would yield useful results.

His experiments in this direction were not entirely satisfactory, but he was able, shortly afterwards, to resume the research on a new basis. In 1879, Prof. Hughes published an account of the Induction Balance which he had recently devised. He had found that equal and similar volumes of various metals exercise widely different effects on induced currents in a coil of wire. These induction-balance effects had also been shown to depend mainly on the electrical resistances of the metals or alloys under examination. These being in many cases largely influenced by minute differences of composition, it was soon recognised that the method could have but limited application in the use for which it was hoped it might be available. The varying molecular condition of alloys of the same composition was another factor which tended to obscure the induction-balance effects due to small differences in composition.

Although these experiments had been primarily directed towards devising

a method which might be supplementary to that of the ordinary process of assaying, by enabling the standard of coins to be verified without destroying their integrity, they, nevertheless, yielded scientific results of importance in other directions.

Roberts-Austen was able to show that in the case of alloys of copper and tin the curve of conductivity for heat corresponds closely with that representing the induction-balance effect. The paper in which these results were published shows what a remarkable insight he had already obtained into the constitution of the copper-tin alloys.

This work affords an early instance in which a distinct relation between properties was found. Such relations he constantly sought, and, as later work shows, successfully found in his prolonged studies of the constitution of alloys, which furnished valuable evidence in support of general principles.

WORK AT THE MINT, 1880-1890.

At the beginning of the second decade of Roberts-Austen's work at the Mint an important addition was made to the duties which he was called upon to perform.

1880. In the month of April, 1880, he was appointed by the Lord President of the Council to the Chair of Metallurgy at the Royal School of Mines. This office had long been held with much distinction by Dr. Percy, who may be said to have created an English literature of metallurgy.

This appointment was made with the full consent and approval of the Lords Commissioners of the Treasury, as appears from the following extract from the Deputy Master's Report for 1880 :—

"In reply to an enquiry addressed to me by their Lordships' directions, I reported that, not only would these duties not be incompatible with those already devolving upon Mr. Roberts, but that this Department could not fail to derive advantage from the appointment of the Chemist of the Mint to a position in which, as Professor, every advance in metallurgical science must of necessity come under his notice."

The year 1880 is noteworthy, also, as marking the commencement of the long series of researches into the properties and constitution of steel, which occupied him almost continuously until the time of his death in 1902.

An investigation was made into the composition and properties of the steel used in the manufacture of dies.

Frequent allusion had been made in earlier Reports to the difficulty which had been experienced in obtaining suitable steel for this purpose, and it had long been felt that the rough method of ascertaining the fitness of steel for conversion into dies, hitherto practised in the Mint, should give place to more trustworthy and scientific tests, while at the same time a more accurate knowledge should be obtained of the composition of the metal which is found to possess the greatest strength and durability.

This investigation, the results of which are set forth in the Report for 1880, involved an examination of the conclusions which had been arrived at by such authorities as Kirkaldy, Akerman, Deshayes, Wohler, and Kennedy. The experiments were continued in the following year, and the question as to the most suitable kind of steel which could then be obtained for the manufacture of dies was definitely settled.

This enquiry incidentally showed the great importance of studying the conditions which affect the hardening of steel, and Roberts-Austen was requested by the Institution of Mechanical Engineers to undertake certain experiments with a view to throwing light on this question. The results established by these early experiments were embodied in a paper which was published in the Proceedings of that Institution in 1881.

This work marks the beginning of his association with this Institution, which in later years yielded such important results.

During the twenty years which followed, the Institution of Mechanical Engineers, as a body, gave him its unwavering support, and by its generosity he was enabled to carry out the work which is embodied in the remarkable series of contributions to the Proceedings of that Institution known as the Alloys Research Reports.

Plate I.] [*To face page* 12.

The Royal Mint, Tower Hill.

Associated with Roberts-Austen on the same Committee in these early days was Sir Frederick Abel, who published simultaneously the results of experiments made with a view to ascertain what changes occur in the condition in which the carbon exists in steel when it is hardened, tempered, and annealed.

At about this time experiments were undertaken in conjunction with Mr. (now Sir) Thomas Wrightson with a view to determining the densities of metals in the fluid state. The importance of such work was clearly recognised by Roberts-Austen, and it is to be regretted that, in the interval which has elapsed since 1881, very little has been done to confirm and extend the work which was then accomplished.

Dr. Henry Schliemann's work on Troy, published in 1880, embodies at some length the results of analyses made by Roberts-Austen of certain objects of bronze, gold, and silver, which possessed special interest, as they appeared to have been used for the purposes of currency.

1881. In 1881 occurred the re-organisation in the establishment of the Assay Department, to which reference has already been made (p. 6). The experience of ten years having satisfied the Master of the Mint that the necessity for maintaining two separate Assay Offices no longer existed, recommendations were made that the two offices should be combined under the responsibility of one Officer. Thus the responsibility for all the assay work performed in the Mint devolved upon Roberts-Austen, and his title from this time became that of "Chemist and Assayer of the Mint."

Several minor changes in the work of the Department followed this re-organisation. For instance, the ancient method of reporting the composition of gold ingots by the "carat" system, which had survived from the earliest times of which there are Mint records, was replaced by the more convenient decimal system which had already been employed in the Australian branches of the Mint and in foreign countries. Another change which was effected was the general adoption of the Gay-Lussac or "wet" method of assaying silver for all purposes, and not merely in checking the composition of bars and coins as hitherto.

1883. During the year 1883 the preliminary results of a research on the "diffusion of metals"—that is, the rate at which metals, in a molten state, will interpenetrate independently of the action of gravity—were communicated to the British Association. In the following year further results were embodied in a paper read at the Montreal Meeting of the same Association.

In conjunction with the Superintendent of the Operative Department, a lengthy investigation was also undertaken of the comparative rates of wear of coins of different metals and alloys, the result of which formed the subject of a Memorandum, which was published in the Mint Report for that year.

In a series of Cantor Lectures delivered before the Society of Arts, he collected from various sources, both ancient and recent, many facts of interest connected with the alloys used for coinage, and with the history of coinage generally. An opportunity was thus afforded for presenting in a popular form the main facts connected with the history of monetary alloys, and for tracing the developments of the appliances used for coinage, from the early types of machines which were either devised or employed by the great artists

of the sixteenth and seventeenth centuries, Leonardo da Vinci, Cellini, Briot, and Simon. Portions of these lectures are reproduced on pp. 29-66.

1884. During the autumn of 1883 he visited the principal Mints and Assay Offices of the United States, in company with the Deputy-Master (Sir Chas. Fremantle). The information obtained from a similar visit to European Mints in 1870 had been of much value, and it appeared desirable that a fuller knowledge should be gained, by presonal examination, of the methods in use in the American Mints, and of the details of such improvements of practice as had been introduced in the various establishments. A further object of enquiry, however, was to ascertain what were the precise regulations in force for the receipt and treatment of gold and silver, and with what results the Government provided for the conversion of the precious metals into stamped bars of varying weight and fineness.

A lengthy report on this enquiry appeared in the 15th Mint Report (1884).

1885. During the year 1885 a series of experiments was conducted, in which he submitted to rigorous tests the results obtained by Professor Spring, of Liége, in compressing finely divided metals. The original results, which were of much interest, especially in connection with coinage operations, were confirmed.

In conjunction with the Superintendent of the Operative Department (Mr. Hill), he ascertained what is the effect produced by small quantities of metallic impurity upon the tensile strength of standard gold. These experiments are specially noteworthy, as they represent the first attempts made by Roberts-Austen to obtain accurate data as to the effect of impurities on the mechanical properties of metals. From these experiments he developed, in later years, work in the same direction which will always be associated with his name. The influence of "traces," or the effect of the relatively small on the relatively great, was the consideration which guided him in most of his subsequent work.

About this time he became associated with Mr. Alfred Gilbert, the distinguished sculptor, in a matter which was of the greatest possible interest to him, and which appealed in a special way to his artistic tastes. Gilbert was anxious to revive interest in the art of casting, by which some of the earlier medals, and especially the Italian series of the fifteenth century, were produced. With the resources of the Metallurgical Laboratory of the Royal School of Mines at his disposal, Gilbert was able to illustrate a brief, but complete, series of lectures which he delivered before the leading sculptors and art workers of the country. Stimulated, no doubt, by this association, Roberts-Austen began to study the methods by which the Japanese obtain the "patinas" of wide range of tint, for which their metal work is remarkable. To this pursuit he devoted much time. The superficial tints of metals and alloys, upon which the beauty of medals in no small measure depends, was then but little understood, and had not previously received the attention which it deserved. The tinting of copper discs, from which the so-called "bronze" medals are struck, was conducted by merely empirical methods, often uncertain in their results, and practised by but few workmen. His experiments were attended with much success, and all the varied tints on a plaque of native Japanese workmanship were imitated. Further experiments were made in producing the banded alloys known to the Japanese as

Moku-me or "wood-grain." The results of these investigations formed the subject of a lecture delivered at the Royal Institution.

Another instance of important work which had its origin in the necessities of Mint practice is afforded by his experiments on

1886. electro-deposited iron.

In preparing the dies for the Jubilee coinage, difficulty was experienced in reproducing the designs in the reducing machine. It had been the practice hitherto to employ in the reducing machine reproductions of the plaster models obtained either by casting or by the electro-deposition of copper. Such electrotypes, although reproducing with great fidelity all the details of the original design, were too soft to withstand the action of the pointed instrument passing over them in the course of the ordinary process of transference to steel in the machine. In these circumstances Roberts-Austen suggested that solid electro-deposits of iron should be used, and having, some years previously, acquired a knowledge of the process from the late M. de Jacobi in St. Petersburg, he succeeded in obtaining excellent reproductions of the models in hard iron.

The experiments on this electrolytically deposited iron were continued in the following year, and measurements were made of its permeability to magnetism by means of Hughes' induction balance. It was shown that this property in electro-iron rises considerably on annealing, and that the low permeability of the metal when unannealed is due to the imperfect state of aggregation of the deposit.

Certain of the deposits were used by Dr. John Hopkinson in his determinations of the magnetic behaviour of electro-iron, and the results were embodied in a paper communicated to the Royal Society.

The work on electro-iron at this time may be said to have been the beginning of researches which subsequently led to his classical study of the allotropy of iron.

At the request of the Council of the British Association, he delivered a lecture in September, 1886, to the operative classes in Birmingham on the "Colours of Metals and Alloys." In this lecture he gave to art-metal workers the results of his experience in carrying out the experiments on art-metal work, which have been referred to on the previous page (see also pp. 361-371).

At the request of the President of the Board of Trade, he served on a Departmental Committee appointed to enquire and advise upon the

1887. arrangements requisite to give effect to the provisions of those sections of a Merchandise Marks Act which related to the assay and marking of gold and silver wares.

In order to carry out the instructions given to the Committee, it was necessary to visit the several assay offices which were then existent in Great Britain and Ireland. This visit was the first official visit since 1851.

The influence of small quantities of impurity on the physical properties of metals had frequently formed the subject of references in the Mint Reports. Roberts-Austen had long wished to ascertain whether the remarkable action of impurities on metals is governed by any known law.

By employing very pure gold, contaminated with small but definite amounts of metallic or other impurities, he satisfied himself that the effect of the added elements on the tenacity and extensibility of gold bears a direct relation to their atomic volumes. The influence of nineteen elements on

gold were examined from this point of view, and it appeared to him at this time almost certain that the action of impurities is controlled by the law of periodicity of Newlands and Mendeléeff, which was then rendering so much service in the study of other chemical and physical phenomena. He predicted that if these generalisations should prove to be correct and to be applicable to other metals than gold, many obscure but important points would be satisfactorily explained. His results were communicated to the Royal Society, and are reproduced on pp. 266-281. Mendeléeff himself expressed his belief in the probability of the theory which Roberts-Austen had advanced.

Subsequently M. Osmond, whose eminence as a metallurgist had already been recognised, satisfied himself, by an elaborate research, that the conclusions at which Roberts-Austen had arrived rested on a sound experimental basis, and were applicable to iron and steel.

In the light of modern tendencies to correlate all physical properties of elements as periodic functions of their atomic weights (see Richard's "Faraday Lecture" to the Chemical Society, 1910), it is somewhat surprising that this work has not been taken up by others and carried further. There seems considerable reason for hoping that in the future this will be done, and acknowledgment will be made of Roberts-Austen's place as the pioneer of these generalisations in relation to metallurgical problems.

At the request of the Electrolysis Committee of the British Association he prepared a report describing certain attempts to electrolyse alloys (*Brit. Assoc. Report*, Manchester, 1887, p. 341). The experiments, as a whole, tended to show that the constituents of an alloy cannot be separated by an electric current. Previous experiments made by Obach and by Haga on certain amalgams and on lead-tin alloys also led to the same conclusion. He pointed out at the time the scientific importance of ascertaining the effect of electric currents on the constituents of molten alloys, and made efforts to ascertain also whether there is a group of bodies between true alloys and true electrolytes in which some gradual change from metallic to electrolytic conduction can be proved to exist.

1888. Changes in the practice of the bullion trade, by which the weights of the ingots sent to the Mint for coinage were increased from 200 to 400 ozs., afforded an occasion for re-opening the question of the possible liquation and consequent lack of uniformity of composition of such ingots. Reference has already been made to the care with which the question was considered in 1873 during the preparation of new Trial Plates, which were to constitute the official standards of reference. Exhaustive experiments were now made to ascertain whether an assay piece, cut in the usual way from these larger ingots, represents its composition as fairly as it does that of the smaller ones. The conclusion arrived at was that no sufficient evidence could be found to show that gold of such fineness as that received at the Mint, alloyed with silver and copper and properly mixed in the molten state, is not practically homogeneous when solid. Results were shortly afterwards published by M. Peligot in Paris, which pointed to the same conclusion (*Bull. de la Soc. d'encouragement*, iv., 1889, p. 171).

The Report of a Royal Commission on the "Recent Changes in the Relative Values of the Precious Metals" (*Parliamentary Paper*, *C.* 5099,

1887, p. 62) contained the evidence given by Roberts-Austen on the cost of production of silver. This evidence attracted much attention in America, and led to an elaborate enquiry of considerable interest to political economists. The estimate of the cost of production of silver, which was made on the basis of the results of this enquiry, was singularly close to that made by Roberts-Austen, whose figure was necessarily based on comparatively meagre data.

1889. In this year he was appointed a member of the Mansion House Committee of the British Section of the Paris Exhibition, acting also as a Juror in the Metallurgical Group.

WORK AT THE MINT, 1890-1902.

The year 1890 marks a very important development in the nature of the work which Roberts-Austen set before himself. It was then that he began, at the request of the Institution of Mechanical Engineers, to extend the investigation which he had previously made on the application of the periodic law to the mechanical properties of metals.

1890.

At the outset of the enquiry it became necessary to obtain accurate thermometric readings at high temperatures, and the pyrometer devised by M. Le Chatelier, depending on the use of a thermo-electric couple, was now adopted by Roberts-Austen, and afforded at once a means of conveniently and accurately measuring high temperatures far in advance of the troublesome and inaccurate calorimetric methods which he had used with so much patience as early as 1873. The temperature being indicated by the amount of the movement of a ray of light reflected from the mirror of a galvanometer on to a graduated scale, it was desirable, for the purposes of the investigation in question, to read the movements of the ray of light automatically, and Roberts-Austen effected this by photographic means.

This adaptation of the Le Chatelier pyrometer is the most distinctive implement of research devised and employed by Roberts-Austen and his assistants, and one which furnished him with the most striking results.

It soon became evident that curves so obtained would afford further evidence as to what happens during the cooling of masses of alloys. Those which were first examined were, quite naturally, the alloys of silver and copper which are used for coinage.

He had already made investigations respecting these alloys (*Proc. Roy. Soc.*, vol. xxiii., p. 481, 1875), and he was now able to examine evidence of the molecular re-arrangement which they undergo during solidification. The results of a memorable research by Guthrie (*Phil. Mag.*, vol. xvii., p. 462, 1884) had led him to the conclusion that certain alloys in cooling "throw off atomically definite bodies, leaving behind a fluid mass which is not definite in composition"; so that, ultimately, the most fusible alloy of the series, which he called the "eutectic alloy," is left, and in it "the proportions between the constituent metals are not atomic." Guthrie's experiments dealt only with alloys of low melting points, such as the "fusible" metals. Roberts-Austen now took up the work where Guthrie had left it, and by his photographic records of the rate of cooling, as measured by the platinum and platinum-rhodium thermo-couple, he was able to show at what temperatures groups of alloys solidify and fall out of solution from the molten mass. At the same time, he was able to obtain evidence as to the probable composition of the eutectics in alloys of high melting point, by means of the thermo-couple, as readily as the earlier experimenters had done in the case of alloys of low melting point, by placing an ordinary mercurial thermometer in a bath of the fused metal.

The measurement of high temperatures continued to form the basis of investigations during 1891. A series of researches on the alloys of the precious metals of which these investigations formed a part suggested certain experiments in connection with the manufacture of ordnance which were carried out at Woolwich. These experiments arose from the remarkable similarity which was found to exist between the action of impurities on

1891.

gold and on iron. This is the first instance recorded in which Roberts-Austen came into direct association with matters relating to ordnance. Afterwards he was consulted frequently on such matters, and finally, as will be seen, he became a member of a Royal Commission appointed by Lord Lansdowne in 1900 to consider the whole question of Ordnance and Explosives.

Roberts-Austen examined the experimental method, which had been adopted in the Paris Mint, for testing the rates of wear of coins of different alloys. These experiments confirmed the conclusion to which previous investigation, conducted at the Mint in 1883, had led, and incidentally settled a question which had been raised in Parliament by showing that the adoption of the standard of fineness of 900, as used on the Continent of Europe and in America, in place of the English standard of 916·66 (or $\frac{22}{24}$ths), would not add any appreciable time to the period during which a coin is in circulation before it falls below the Least Current Weight prescribed by law.

During this year (1891) he described to the Royal Society a new series of alloys of gold and aluminium, which are remarkable for their intense colour, varying from yellowish-green to purple. The melting points of this series of alloys were also determined. The chief interest attaching to this work was the discovery of a "purple alloy" containing 22 per cent. of aluminium, which was one of the first alloys to be definitely recognised as a chemical compound. The melting point of this alloy was shown to be above that of pure gold, thus constituting what, at that time, was an anomaly—all alloys, other than those containing mercury, having previously been regarded as having melting points below that of the least fusible constituent. These purple alloys presented, therefore, the most important case known at that time of a molecular structure built up entirely of metallic atoms, and the series is of special interest in connection with the history of chemical science.

The investigations which had been commenced in the previous year at the request of the Institution of Mechanical Engineers were published in the form of a report. This report, known as the "First Alloys Research Report" (*Proc. Inst. Mech. Eng.*, 1891, p. 543), mainly deals with the question of whether metals can, like phosphorus, sulphur, and many other bodies, exist in two or more distinct states of molecular aggregation, each with widely different properties peculiar to it. The evidence of such molecular change, which mainly rests on the measurement of the rate at which heat is evolved during the cooling of metals and alloys, though difficult to obtain, was slowly accumulated, and its importance in connection with the mechanical properties of metals was made evident.

This marks the commencement of the work on allotropy, which he subsequently extended to the study of iron and steel, and which provoked bitter controversy among specialists for many years.

The amount of routine work which now devolved upon the Assay Department made it impossible for Roberts-Austen to conduct much
1892. original research work in the Mint without additional aid. He, therefore, gladly accepted the proposal of the Council of the Institution of Mechanical Engineers to place at his disposal the services of two assistants, in order that his investigations on the mechanical properties of metals might be continued. Mr. W. C. Jenkins and Mr. Alfred Stansfield

were accordingly appointed. With their aid the researches made rapid progress, and reference is made in another place to the importance attaching to the generosity of the Institution in thus enabling valuable work to be continued (see p. 132).

At first the work was mainly directed to perfecting the methods of measuring and autographically recording high temperatures, and to studying the behaviour of metals and alloys under thermal treatment.

The main object of the enquiry was the study of the action of small quantities of foreign elements on masses of metal, and the results confirmed the view that the volume of the atom of an impurity has great influence in affecting the mechanical properties of a mass of metal.

The results of the work in perfecting the methods of measuring high temperatures were embodied in a paper which was read to the Institution of Civil Engineers by Roberts-Austen (*Proc. Inst. Civil Eng.*, vol. cx., 1892, part iv.), and for which he was awarded the Telford Prize.

Shortly after the close of the year he made his Second Report to the Institution of Mechanical Engineers.

1893. Early in 1893 the Lords Commissioners of the Treasury directed that he should act as Chairman of a Departmental Committee which was appointed to enquire into the laboratory arrangements of the Customs and Inland Revenue Departments. The work of the Committee proved to be complicated, and its meetings were consequently numerous and prolonged. As the result of this enquiry, their Lordships directed that the whole of the laboratory work of the two Revenue Departments should be united under the control of a Chief Chemist, who should not be attached exclusively to either Department.

At the request of the Secretary of State for India, he served as a member of a Committee appointed to consider the best means of utilising the water power available on the completion of the Periyar Irrigation Works then in progress in the Madras Presidency. Questions of much interest in connection with the use of water power in conducting certain metallurgical operations were dealt with in the report.

The method of autographically recording high temperatures with which, his name had now become associated, was widely adopted, and much appreciated in connection with various industrial operations. Installations of the new instrument in certain large iron works made it possible to collect information which had not hitherto been available respecting the temperatures attained, and the reactions which occur during the smelting of iron.

The possession of an instrument capable of indicating, by autographic time-temperature curves, the nature of the changes which take place during the thermal treatment of metals and alloys facilitated the investigation of delicate problems connected with the molecular structure of metals. It was found, too, to be of no small advantage to be able to determine by pyrometry how far high temperatures can be maintained constant, and the amount of variation in temperature which occurs.

This use of the pyrometer enabled him to resume an investigation on the diffusion of liquid metals in each other, a research which he had begun many years before, and the results of which he had communicated in part to the Royal Society. The work had, however, been abandoned at the time for want of a trustworthy method of measuring high temperatures.

His recording pyrometer continued to be the main appliance, by the aid of which researches were conducted, and the efforts made to
1894. increase its sensitiveness led to results of much interest and importance. It now became possible to obtain information as to the molecular changes which take place in a mass of metal from the moment it begins to cool until it is solid, and even after it has become so. Considerable light was at once thrown on the change in physical properties, such as the brittleness of standard gold, resulting from the presence of a small amount of an impurity.

Many analogous experiments were made, and they led to an important generalisation on the relation between the tensile strength of metals and the temperatures at which metallic and other impurities in them become solid.

His generalisation was worded with some reserve, and may be briefly stated:—

"If the solidifying point of the added element is much lower than that of the mass, the metal as a whole will be greatly weakened, while in the contrary case the metal will be strengthened, often to a remarkable extent. It must not, however, be supposed that the action of the added element is solely due to the degree of fusibility, as cases in which such an explanation does not apply are numerous, but the question is still under investigation."

Experiments were undertaken in conjunction with the Superintendent of the Operative Department, with a view to ascertain the most
1895. suitable conditions for annealing and blanching blanks to be used for coinage. Certain changes were recommended in regard to the practice then in use, and as a result muffle furnaces were adopted in place of the reverberatory furnaces which had hitherto been employed.

The results of the researches on the diffusion of certain liquid and solid metals in each other, which had from time to time occupied his attention during the past eleven years, were communicated to the Royal Society. The Council of the Society directed that they should form the subject of the annual "Bakerian Oration," which he accordingly delivered on the 20th of February, 1896.

Until this work was undertaken very little attention had been directed to the consideration of the molecular movements which enable two or more molten bodies to mix spontaneously and form a homogeneous fluid mass. He pointed out that the alloy of gold and copper used for coinage owes its singular uniformity in composition, not only to the mechanical stirring by which the blending of the gold and copper is roughly effected, but also to the fact that the metals dissolved in each other become spread or diffused uniformly by a spontaneous process.

It was well known that such molecular movement occurs when salts are dissolved in water, and the rate at which various salts dissolve and diffuse in water had been accurately measured by Graham. Very little attention had, however, been devoted to the measurement or even the consideration of the molecular movements in fluid metals, and the absence of direct evidence upon the point is probably explained by the want of a sufficiently accurate experimental method.

Ostwald had stated with reference to the diffusion of salts that, "to make accurate experiments in diffusion is one of the most difficult problems in

practical physics," and the difficulties are obviously increased when working with metals at high temperatures. It was, moreover, well known that the rate of saline diffusion is greatly augmented by a comparatively small increase of temperature, a fact which suggested that the thermal measurement must, therefore, be accurate.

The want of a ready method for the measurement of comparatively high temperatures, which had led to the abandonment of his earlier work, was overcome by his recording pyrometer, the use of thermo-junctions with which rendered it possible to measure and record the temperatures at which diffusion occurred.

The experiments showed that metals diffuse in one another just as salts do in water, and the results were ultimately calculated by the aid of tables prepared by Stefan for the calculation of the results of Graham's experiments on the diffusion of salts.

The belief had long been prevalent that diffusion can take place in solids, although no attempt had hitherto been made to measure the rate of diffusion of one solid metal in another. Gold and lead were the metals chosen for examination, both in the fluid and in the solid diffusion experiments.

The continuation of these experiments led to the recognition of the remarkable fact, which is of much industrial importance, that diffusion of metals can readily be measured, not merely in the molten, but in the solid state.

The question of the suitability of different varieties of steel for the manufacture of dies had been dealt with by Roberts-Austen in
1896. the Annual Mint Reports from time to time.

Hitherto the question had been approached mainly from the point of view of the chemical composition of the steel. From the results of a comprehensive enquiry conducted during the years 1881 and 1882, it appeared to be safe to conclude that steel, which was proved by analysis to contain carbon and manganese in certain definite proportions, and to be free from sulphur and phosphorus, would give satisfactory results when used for this purpose. Such a steel must, however, be subjected to uniform treatment in the preparation of the dies.

Since this work had been done great advance in the knowledge of the constitution of metals and alloys had followed the development of the methods of examining their structure, mainly by the aid of micro-photography. Progress in this direction, as regards iron and steel, had been mainly due to the researches of Dr. Sorby in this country and of M. Osmond in Paris (see *Brit. Assoc. Report*, 1864, part ii., p. 189; *Journ. Iron and Steel Inst.*, No. I., 1886, p. 140, and No. I., 1887, p. 255; *Bull. de la Soc. d'Encouragement*, May, 1895).

It appeared to Roberts-Austen to be very desirable to extend their work to the examination of die-steel. In preparing the specimens of steel for microscopic examination M. Osmond's directions were closely followed.

The results of the microscopic examination of different varieties of die-steel were reproduced in the 27th Mint Report (1896). These photographs (see p. 240) are the first examples published by Roberts-Austen of the evidence afforded by the microscope of differences in the structure of metals resulting from a difference in composition or in the thermal treatment to which the metals have been subjected, and they are especially interesting in this respect at the present time when so many workers are

engaged, in all parts of the world, on this particular branch of metallurgical work.

Roberts-Austen pointed out at the time the importance of such investigations, but it can hardly be imagined that, enthusiast though he was, he could have realised the immense significance of this early work, and the extent to which these micrographic methods would be adopted.

Before the close of the year he completed the Fourth Report of the Alloys Research Committee, of which the late Sir William Anderson, the Director-General of Ordnance Factories at Woolwich, was then the Chairman.

In conjunction with M. Osmond, of Paris, he communicated a paper to the Royal Society during the year on the micro-structure of gold containing certain impurities which affect its suitability for coinage.

In the same year Roberts-Austen was chosen as one of two representatives which the Royal Society was asked to select to serve on a Departmental Committee of the Board of Trade appointed to enquire as to the loss of strength of Steel Rails produced by their prolonged use on railways.

1897. Considerable progress was made with the work of the Departmental Committee, and he submitted a Report of his own experiments which were directed to an investigation of the structure of steel rails as revealed by photo-micrography.

In addition to this Departmental work, he was appointed by the Lords Commissioners of the Treasury to act on a Committee which was formed to enquire whether "it were desirable to establish in this country a National Physical Laboratory." He thus became directly associated with an extremely important development in the scientific resources of the country.

His Memorandum in the Mint Report for this year (1897) is mainly devoted to a description of the methods of treating the surfaces of medals, a matter to which his attention had been specially directed during the preceding year in connection with the Commemoration Medals issued at the time of the Diamond Jubilee. His remarks on the patination of copper medals were of particular interest, and his experiments in this direction led to highly satisfactory and beautiful results. By the adoption of the treatment, of which details were given in this Memorandum, public requirements were supplied at a more rapid rate than would otherwise have been possible.

1898. The small laboratory, which had been fitted up in the basement of the Assay Department originally for the photo-micrographic examination of steel used in the manufacture of dies, continued to be very useful, and the scope of the work carried out was considerably extended.

Reference has already been made to the first photo-micrographs obtained in it, and published in the Mint Report for 1896. The installation served as a model for similar laboratories which were established at the Royal Arsenal, Woolwich, at Sir W. G. Armstrong, Whitworth & Co.'s Works at Elswick, and at the Engineering Laboratory at the University of Cambridge. All the micrographic work entrusted to him, as a member of the Departmental Committee of the Board of Trade, investigating the loss of strength of steel rails during use, was conducted in this laboratory; and later, all the work of similar character in connection with the Alloys Research Committee of the Institution of Mechanical Engineers.

The Ordnance Committee of the War Department supplied him with samples of steel used in the manufacture of guns and armour plate. Photomicrographs of these enabled a comparison to be made of the structure of different varieties of steel then in use.

From this time until his death he continued in active co-operation with the War Office and the Admiralty in elucidating problems which arose from time to time in the manufacture of ordnance.

The Fifth Report of the Alloys Research Committee was published during the year, by the Institution of Mechanical Engineers. It related mainly to the structure and properties of steel, and is dealt with more fully in the section devoted to the work of this Committee (see pp. 132-153).

The establishment of a National Physical Laboratory was sanctioned by the Lords Commissioners of the Treasury, in accordance with the recommendations of the Committee of which Roberts-Austen was a member. The arrangement and administration of this new institution was entrusted to the Royal Society.

1899. In the Mint Report for this year considerable space is devoted to the work which had been involved in the preparation of New Trial Plates to replace those made by Roberts-Austen in 1873, and which had now been used up. The whole question of the accuracy and uniformity attainable in making these Trial Plates was again carefully investigated. Details are given of the steps taken to secure trustworthy results, and also of the endeavours made to overcome the difficulties in attaining uniformity in the distribution of the alloy in the Standard Silver Plate.

Difficulties had again arisen with regard to bullion which, when alloyed with copper and cast into bars for coinage, proved to be brittle. This formed the subject of a further investigation.

In continuation of his experiments on the Diffusion of Metals in 1895, he was able to announce the results of certain experiments on the solid diffusion of gold in lead which had been in progress during the preceding four years, and which were now communicated to the Royal Society.

1900. The pressure of public work arising out of his long-continued researches was now becoming very great, although but little evidence appears in the Mint Reports of the last two years of his life of the great activity which he was displaying in all directions. His position in the metallurgical and scientific worlds had now become such that the demands made upon his time and energies were very severe.

His investigations were now mainly devoted to the steel used for the construction of guns and projectiles in connection with the Explosives Committee of the War Office and Admiralty, on which he had been requested to act by the Secretary of State for War (Lord Lansdowne). Simultaneously with this work, that of the Alloys Research Committee was being actively continued.

1901. Fully occupied as he was at this time with work of far-reaching importance, having but little or no bearing on the operations of minting, it is characteristic of him to find that his last Memorandum in the Mint Reports shows striking evidence of his constant devotion to the work with which he had been associated for 31 years. A detailed account is given of work, which had been carried out under his daily supervision,

directed to obtaining electro-deposited iron copies of plaster casts for the production of "punches" by a reducing machine.

Then follows a short account of some work in connection with the preparation of Trial Plates, which it will be remembered had occupied his attention at the very outset of his career, thus showing that he was striving until the last to ensure that the accuracy of the composition of the coinage, for which he had been responsible for so many years, should be free from even the remote possibility of avoidable variations.

He concludes his Memorandum with these words :—

"This research is one outcome of the experiments on alloys which have so long been conducted in the Mint, and to which reference has been made in former Reports. It may be added that such portions of the investigations as have proved not to be useful in connection with the operations of coinage have been transferred to the National Physical Laboratory, and the first place will be given in that Institution to continuing this work."

A record of Roberts-Austen's work at the Mint would not be complete without some reference to the responsibilities which it entailed. From 1870 until 1902 he was responsible for the composition of over £150,000,000 of gold and £31,000,000 of silver coins.

References to his Memoranda in the Annual Mint Reports are included in this section, and also a series of Cantor Lectures to the Society of Arts on "Alloys used for Coinage." These lectures, together with an article entitled "The Queen's Assay Master," embody many of his researches into the history of the office which he filled for so many years.

REFERENCES TO THE MEMORANDA OF THE CHEMIST AND ASSAYER CONTAINED IN THE ANNUAL REPORTS OF THE DEPUTY-MASTER OF THE MINT.

IN TWO SECTIONS—(1) 1870-1889; (2) 1890-1902.

[The first number (bold type) refers to the number of the Report, and the second number to the page. *E.M.* indicates the Report on European Mints, 1871.]

Mint Reports, 1870-1889.

Mint Reports, 1890-1902.

ADDITIONAL BIBLIOGRAPHY OF WORK NOT CONTAINED IN THE MINT REPORTS, BUT HAVING A DIRECT BEARING UPON COINAGE OPERATIONS.

1870. Report on European Mints.
1871. The molecular arrangement of the alloy of silver and copper employed for the British Silver Coinage.—*Brit. Assoc. Report*, xli., 1871 (sect.), p. 80.
1873. Report of the Committee appointed for the purpose of inquiring into the method of making gold assays.—*Brit. Assoc. Report*, xliii., 1873, pp. 219-222.
1874. On the preparation of Standard Trial Plates to be used in verifying the composition of the coinage.—*Chem. Soc. Journ.*, xii., pp. 197-203, 1874.
1875. Second Report of the Committee for making gold assays.—*Brit. Assoc. Report*, pp. 155, 156, 1875.
1878. Alliages d'or et de cuivre (Trans.).—*Annales de Chemie*, xiii., pp. 133-140, 1878.
1884. Alloys used for coinage—Cantor Lectures.—*Roy. Soc. of Arts*.
1885. Assays—a paper read before the Bankers' Institute, April 15th, 1885.
1887 "The Queen's Assay Master."—*Murray's Magazine*, May, 1887. Also the article "Mint."—*Encyclopædia Britannica*, 9th edition.

Plate II.]

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Research Laboratory, Royal Mint.

ALLOYS USED FOR COINAGE.

A series of Cantor Lectures delivered before the Society of Arts in 1884.

FIRST LECTURE.[1]

[This lecture dealt mainly with the mechanical operations of coinage, and has therefore not been reproduced in full. The following abstract appeared in the *Chemical News* for March 21, 1884.]

The lecturer pointed out that, although the gold coinage of this country is estimated (1884) to consist of no less than 700 tons of an alloy of gold and copper, information as to the nature and composition of the alloys used for coinage is far from being widely diffused. The views of many people on this important subject may still be expressed by the words of William Stafford, one of the earliest of English political economists, who, writing in 1581, makes a Knight "confesse that he could not perceave what hinderance it should be to the realme to have this metal more than that for our coyne," provided it "be stricken with the Prince's seale."

The operations conducted in a modern Mint are chiefly remarkable for the extreme care and accuracy with which they are conducted. This being the case, it was considered advisable to devote the first lecture to tracing the steps by which the machinery and appliances now in use have been arrived at; but it is very difficult to describe the history of the mechanical side of coining chronologically, because progress has been by no means continuous, as certain types of machines have survived persistently in some countries and have been abandoned in others often to be again introduced with or without modification. (Illustrations of this fact were then given.) It is safe, however, to conclude that, while in civilised countries, at least since the thirteenth century, the designs of coins have always fairly represented the artistic culture of the periods at which they were struck, the appliances used in their manufacture have at times been distinctly behind the mechanical science of their days, as indicated in other technical arts. For the last fifty years, until the early part of 1882, the Mint in this country presented a striking example of this fact, as its machinery was admitted to be antiquated, while the general progress of mechanical science during the same period was probably greater than at any other time. It was further pointed out that, viewed from a modern standpoint, there have been periods during which the work of the metallurgist in the purification of the precious metals, and in verifying their standards of fineness, has been greatly in advance of that of the artist who engraved the dies or the mechanician who struck the coins.

The methods adopted by the Greeks in striking coins were indicated, and the lecturer stated that, excepting some uncertainty as to the nature of the metal or alloy used for the manufacture of the Greek dies for coining, we know, thanks to the labours of M. Mongez, nearly as much of the methods adopted as if we had seen the ancient coiners at work.

The casting of coins, as conducted in late Roman times, was then described, and, as instances of curious survivals of casting operations, details were given of the production of bars of metal by casting in moulds of wet canvas, as

[1] *Journ. Soc. of Arts*, 1884, vol. xxxii., p. 804.

seen by Jars in the Mint at Zellerfeld in the middle of the last century, and of the actual casting of coins of bell-metal in Paris in 1792.

Recent methods of coining were illustrated by cutting the discs of metal by means of an appliance formerly used in the Mint in the Tower of London, and by striking them by a press devised in the Paris Mint early in the present century. The lecturer said it had been contended that art had suffered serious loss by the replacement of the old hand-struck money by coins struck by machinery. It was, therefore, not a little remarkable that the artists who were connected with Mints appear to have been the very people to insist on the introduction of mechanical improvements. For instance, to take only the comparatively well-known names from those that were mentioned, Benvenuto Cellini described in 1568 the screw press, which, in a form modified by the genius of Boulton in 1790 so as to enable it to be worked by steam power, has only just been abandoned in the Mint of this country. Leonardo da Vinci, as Dr. Richter has recently shown, devised in 1515, for use in the Roman Mint, a method of "cutting out" discs of metal for conversion into coin, which was a great advance on the crude methods employed in the sixteenth century. Briot, Engraver-General of the Paris Mint, invented a machine in the reign of King Charles I., which depends upon a principle definitely adopted in the new lever coining-presses of the English Mint; and his pupil Simon, the greatest engraver England has ever had, employed an elaborate mechanical device which enabled him to produce one of the most beautiful coins known. In order to meet the objection that the artistic side of minting was hardly within the province of the chemist, the lecturer quoted Biringuccio, one of the greatest of the early metallurgists, whose advice to a Mint Master, written in 1540, might be briefly stated as follows:—"If the coins are very accurate as regards standards of fineness but small profits can be made, while if too much base metal is introduced the execrations of the people will follow; but special care should be devoted to the preparation of dies for striking artistic coins, with a view to give the people pleasure in things they are obliged to use."

ALLOYS USED FOR COINAGE.

SECOND LECTURE.[1]

The meaning of the word alloy, in mint language, is different from that ordinarily accepted in scientific phraseology, as it is applied to the base metal added to a more precious one, and not to the mass, which may be either molten or solidified, of the mixed metals. This use of the word has been fostered by the way in which it has, from time to time, been employed in ordinances that have regulated the composition of the coin, and in the indentures made between the Sovereign and the Master of the Mint. It has also been perpetuated by the first schedule of the Coinage Act, 1870, the legislative enactment which guides the currency at the present time. The earliest of these ordinances extant, that given by King Edward I. to Gregorie Rokesley, prescribes that a pound of silver money shall contain "11 ounces, 2 easterlings (dwts.), and 1 farthing of silver, and the other 17 pence 3 farthings to be 'lay'[2]—that is, 'alloy.'" Biringuccio used the word with perfect accuracy in the sixteenth century. "I have told you," he says,[3] speaking of the gold alloys, "that an alloy only signifies an intimate association (*damicabile amicitia*) of one metal and another." The author of an interesting little work entitled "A Touchstone for Gold and Silver Wares,"[4] usually employs the word in the Mint sense, as when he says, "Silver having too little alloy would be too soft, so too much alloy would make it brittle like brass;" but Cramer,[5] a later writer, is scientifically accurate in calling a mixture of gold with silver a "white alloy." With regard to the derivation of the word, it may be sufficient to point out that the old French *alei* was retained in the Norman as *alai* or *allai*, whence our word allay. Through the erroneous fancy that the French *aloi* was equivalent to *à loi* (to law) the word, meaning originally simple "combination union," came to be used specially of the mixing baser metal with gold and silver in coin, so as to bring it to the recognised standard, and hence of the standard itself.[6] The French word comes from *alleium* or *alaium*, the original being probably *ad-ligo* (alligo), to bind to. Used in the Mint sense, the relation of the word "lay" or "allay" to the Teutonic *linderen*, to lessen, as pointed out by Sir John Pettus,[7] is suggestive, as it is in the sense of a precious metal "lessened" in value, that "alloy" is retained in the Mint at the present day; but I may be permitted to repeat that this is an inaccurate use of the word, and that a sovereign should be viewed as a coined disc of an alloy of gold and copper, the union of the two metals constituting the alloy. The word sterling, again, deserves a brief notice, and I will only quote Stow,[8] as his explanation, adopted by later writers, is probably the correct one. He says, "but the money of England

[1] *Journ. Soc. of Arts*, 1884, vol. xxxii., p. 835.
[2] Ruding, vol. i., p. 192.
[3] Original Edition, p. 73, 1540.
[4] Second Edition, p. 8, 1679.
[5] "Elements of the Art of Assaying Metals," by J. A. Cramer, M.D. Second Edition, p. 118. London, 1764.
[6] A New English Dictionary, edited by J. A. H. Murray, Clarendon Press, 1884.
[7] "Fleta Minor," Essay explaining Metallic words, see "Allay" in the appendix. London, 1683.
[8] "A Survey of London," by John Stow, p. 52, 1603.

was called of the workers thereof, and so the Easterling pence took their name of the Easterlings, which did first make this money in England in the reign of Henry II., and thus I set it down according to my reading in Antiquitie of money matters, omitting the imaginations of late writers, of whom some have said Easterling money to take that name of a starre stamped on the border or ring of the penie: other some, of a bird called a stare or starling stamped on the circumference, and others (more unlikely) of being coined at Stiruelin or Starling, a towne in Scotland." Lowndes adopts this "Easterling" view of the origin of the word sterling,[1] and supports it by reference to a very old treatise "entered at large in the Red-book of the Exchequer, in the time of King Edward III.," and he considers that the words "sterling" and "standard" are synonymous. Similar arguments are adduced at great length, with abundant references to authorities, in Hearne's "Curious Discourses."[2] The word sterling was, however, probably used to distinguish a definite alloy of silver and copper from certain other alloys containing less of the precious metal.

Throughout these lectures the words "standard fineness" indicates the amount of "fine" or pure metal present in any given alloy, and the degree of fineness will be expressed decimally, pure gold or pure silver being considered to be 1,000.

The reasons for the use of alloys, in preference to pure metals, are somewhat complex. In early states of civilisation coins are generally made of more or less pure metal, but a nation does not advance far in its history before the very important fact is recognised that alloys are more durable than pure metals, and that their substitution for pure gold or silver affords a notable source of revenue. In cases where the coinage is in any degree international, the adoption of a low standard by one nation has to be followed by its neighbouring nations, in order to prevent loss, and to facilitate commerce by avoiding the necessity for tedious calculations as to the rate at which coins may circulate in the respective countries. It is still possible, though not to the same extent, to make profits in the way indicated by Sir John Pettus, who, writing in the seventeenth century, observes, "it is good for a traveller to be skilful in different alloys, whereby, as a friend of mine told me, that he carried out £100 with him, and by his art of exchange in countries where alloys differed, he bore his charge of travel, and brought his stock home again."[3] A well-known modern instance of such a system is presented by the action of the first Europeans trading with Japan in virtue of the Treaty of 1858, who, availing themselves of the fact that the gold coins of that country were current at considerably less than their true value in silver, bought the gold kobangs then in circulation for about one-third of their actual value, and realised large profits.

The actual melting of the precious and base metal is effected in small furnaces with natural draught, and the crucibles employed are usually made of a mixture of graphite and fireclay. The capacity of the crucibles is very varied; those used in this country for melting gold hold about 1,200 ozs.,[4] and the crucibles for melting silver 4,000 ozs. Gaseous fuel is sometimes

[1] "Essay on the Amendment of the Silver Coins," p. 16. London, 1695.
[2] Edition of 1771, vol. i., pp. 10 and 13; and vol. ii., pp. 315 and 379.
[3] Fleta Minor, Appendix, word, "Money."
[4] Larger amounts are now melted in one operation (1913).]

though rarely, employed in mints,[1] and I only know of one mint in which metal is melted on the open bed of a reverberatory furnace, and then, of course, the alloy to be formed is only bronze. The use of such furnaces would present some advantages, but as a considerable amount of metal would be, temporarily at least, hidden in the more or less leaky furnace bed, it becomes absolutely necessary to employ crucibles for melting the precious metals.

With regard to the choice of the base metal to be added to the precious, many conditions have to be taken into consideration. The resulting alloy must be of good colour, must be ductile, and must not exhibit any traces of brittleness. In the case of gold, silver forms a very ductile alloy, but then, as we have seen, it sensibly lowers the colour of the gold. Copper, on the other hand, heightens the tint, and has the advantage of yielding a durable as well as ductile alloy. A triple alloy of gold, silver, and copper may be made of delicate tints, but a triple alloy is difficult to assay, and it is undesirable to complicate the accounts of a mint by the use of two precious metals and a base one in the same alloy, therefore a single base metal, copper, is now almost universally used.

It has long been known that the union of two or more metals produces a result which often differs more in physical properties from either of its constituents than they do from each other. Copper and tin, for instance, alloyed in definite proportions, yield alloys of a wide range of properties, and there is hardly any fact more remarkable in the whole range of metallurgy than the enormous influence exerted on a large mass of metal by a small quantity of another metal or metalloid.

From the Mint point of view, the properties which it is most desirable to secure are—1, Ductility; 2, Durability; 3, Uniformity of composition.

In addition to these, the alloy is expected to be sonorous—that is, the coin struck from it must have the true "ring"; and, finally, it must possess exactly the degree of viscosity which will enable it to flow, under pressure, into all the fine lines of an engraved die, while at the same time the metal must have sufficient rigidity to retain its impression when submitted to rough usage. This question of the flow of metals has been beautifully worked out by M. Tresca,[2] who has shown that when metals and alloys are submitted to compression, they so closely resemble fluids in their behaviour, that the shape they will assume can be deduced by calculation. In coining a disc of metal, the engraved work of the die forms a series of channels designed to facilitate the flow of the metal of which the coin or medal consists, and to guide it in the required directions. In the compression of a "blank" between dies, the portions not to be brought into relief by the action of the press are reduced in thickness for the benefit of the neighbouring raised portions, the metal literally flowing from the level parts to the reliefs.

I once heard Mr. Ruskin say in a lecture:—"You stamp the effigy of a cow on a pat of butter, why don't you stamp the bee on the honey?" Simply because one is much more viscous than the other, and will not retain a shape given to it; and from the coining point of view this is precisely true of lead, which rapidly becomes defaced by only a moderate amount of wear,

[1 Gaseous fuel is now employed at the Royal Mint (1913).]

[2 Paper read before the Society of Mechanical Engineers of Paris; translated, *Journ. of Franklin Inst.*, Philadelphia, 1878, vol. lxxvi., pp. 263-326.

and in a less degree of pure gold. It is absolutely necessary to add some other metal which will form a more or less rigid alloy.

With regard to the sonorous property of the alloys used for coining, if two rods, one of pure silver, and the other of the alloy of silver and copper, known as standard silver, be hung close together, one will ring loudly when struck, while the other gives a comparatively indistinct sound. The best indication, however, of the total difference between the molecular grouping of a pure metal and an alloy, is afforded by their electrical behaviour.

It will, I trust, be evident that the base metal added to gold or silver may be regarded from two distinct points of view; either as a useful constituent of the coin, which enables it to resist wear and hinders the obliteration of its impression, or, if coins containing base metal are made current at more than their intrinsic value, as a source of gain to the rulers of a country. With regard to the actual standards of fineness which have, from time to time, been employed, it may be pointed out that, in the numismatic history of the world, endless combinations of precious and base metal have been represented. Pure gold and silver have been used, either singly, or alloyed with each other, or alloyed with copper, the latter metal, in turn, being sometimes employed with only infinitesimal additions of precious metal.

The alloys actually used for coinage at the present time are not numerous, and it may be well to begin the consideration of such as are specially important by tracing the steps which led to their adoption.

In the case of both the gold and silver currency of this country, the adjustment of the relative proportions of the precious and the base metals was undoubtedly guided by the particular systems of weights used. To take the silver coinage first, the fineness of alloys of this metal has from very early times been computed by divisions of the troy pound, which weight is still retained in weighing gold and silver. The Commissioners appointed in 1868 to inquire into the conditions of the Exchequer standards, state that "the troy pound is said to have been derived from the Roman weight of 5759·2 grains, the 125th part of the large Alexandrian talent, this weight, like the troy pound, having been divided by the Romans into twelve ounces;" and they add, "the troy weight is universally allowed to have been in general use from the time of King Edward I. The most ancient system of weights in this kingdom was that of the moneyer's pound, or the money pound of the Anglo-Saxons, which continued in use for some centuries after the Conquest, being then known as the Tower pound, or sometimes the goldsmith's pound. It contained twelve ounces of 450 grains each, or 5,400 grains, and this weight of silver was a pound sterling. The Tower pound was abolished in 1527 by a statute of King Henry VIII., which first established troy weight as the only legal weight for gold and silver. . . . From that time to the present our system of coinage has been based on the troy weight." [1] The computation of the standard fineness of alloys of gold is based on the singular "carat" system of weights, the origin of which is popularly believed to have been derived from the weight of an oriental plant seed. Mr. H. J. Chaney, who is entrusted with the duties of the office of Warden of Standards, informs me that "its history is not easily traced, but that the origin of the carat

[1] Third Report of Commissioners. Parliamentary Paper, c. 30, p. 3, 1870.

is doubtless Grecian. The *ceratium* was a small Greek weight."[1] It is uncertain whether the use of the carat came to us through the Arabian alchemists, or through the Roman mints, and the exhaustive inquiries of Vasquez Queipo do not throw much light upon the point; but with regard to the supposed derivation of the weight from the seed or bean, Mr. Chaney thinks "it is more probable that the Greek *Keration*, and the Arab *Kyrat*, were applied to the beans or seeds by the native merchants, who made them serve provisionally as weights."

It has been necessary to offer the foregoing explanations, because the expression of the varying standards of fineness, either in the "carat and grain" system or in the "ounces, pennyweights, and grains" of the troy system, is somewhat obscure to those who are not familiar with their use, and although the decimal system will be adopted for the purpose of this lecture, it will be difficult to avoid references to the older methods of computation.

In 1790, Mirabeau, in an elaborate memoir submitted to the National Assembly in France,[2] urged that the decimal system should be applied to the coinage, and, as will be shown subsequently, his views were adopted in 1794. The use of this system spread rapidly over the Continent, but the computation of the fineness of gold alloys by the system of carats and grains survived in the English Mint until 1882, when the decimal system was introduced.[3]

With these remarks we may proceed to the consideration of the alloys used for coinage in early times.

It may be convenient to begin the history of the alloys used for coinage with the employment of the natural alloy of gold and silver, to which the ancients gave the name of electrum, native gold being always associated with silver, which is sometimes present in sufficient quantity to sensibly lower the colour of the more precious metal, and to cause the gold tint to disappear almost entirely when it exceeds one-third part of the mass.

Dr. Schliemann describes[4] three pale yellow rod-like bars, each 4·33 inches long, provided with fifty to sixty equi-distant horizontal incisions, at right angles to the length of the rods, which probably indicated their value, and facilitated their subdivision into definite portions. Dr. Schliemann kindly permitted me to analyse a small portion of one of these rods, which was found to contain 651 parts of gold, and 334 parts of silver in 1,000 parts, and small quantities of copper and lead.

In a dissertation on the Homeric talent, Dr. F. Hultsch states that it weighed 16·8 grammes, or a little above ½ oz. troy, and was the prototype of the oldest gold stater, coined in the beginning of the seventh century B.C., at Phocea, and other cities of Asia Minor.[5] I have already referred to the coined nuggets of electrum which may have been adopted for purposes of currency long before the use of coined money; but, as M. Lenormant points

[1] Quoted by Mr. Chaney, in a letter to me, from "Lucae Paeti de Mensuris et Ponderibus," Venetiis, 1573, p. 88.

[2] "Collection complette des Travaux de M. Mirabeau l'ainé à l'Assemblée Nationale," Paris, 1792.

[3] 13th Annual Report of the Deputy Master of the Mint, 1882, p. 46.

[4] "Ilios," p. 496. London, 1880.

[5] "Griechische und Römische Metrologie." Berlin, 1882. Quoted by Dr. Schliemann, "Troja," p. 113. London, 1884.

out,[1] in the series of coins of the kings of Lydia, gold and electrum were coined simultaneously, as distinct metals, having distinct monetary values.

The numerous analyses made by Dr. Rauch[2] and others have placed at our disposal much accurate information as to the standard fineness of the alloys used for coinage in Greek and Roman times. M. Lenormant,[3] who devotes a considerable portion of his elaborate work to the consideration of this subject, observes "that in the Hellenic world the coins of gold and silver were remarkably pure, the gold coins sometimes contained only 3 parts of silver in the 1,000, which represented the highest degree of purity attainable by the method of refining then in use.[4] In the coins of Darius a little base metal was intentionally introduced, but its amount did not exceed 30 parts in the 1,000, and, speaking generally, the Grecian silver coins contained considerably less base metal than coins issued in modern times. The standard of the tetradrachms of Athens, at the best period, varied from 983 to 986, while those of the second series fell only as low as 966, and these contained 2 parts of gold in the 1,000, as well as the 32 parts of copper. A series of Greek coins struck in Italy and Sicily in the sixth century before the Christian era, vary in fineness from 910 to 980. At the end of the coinage at Tarentium, the standard was sensibly lowered, for a didrachma assayed by Dr. Rauch was found to have only the fineness 880, but M. Lenormant observes that, in the entire series of Asiatic coins before the conquests of Alexander, there is no essential change in the standard of silver, which is uniformly high, although instances are met with of coins of as low a standard as 709. With regard to Roman money, I will only quote Lenormant's statement that the gold of the Republic was always pure, and that Imperial gold coins, until the time of Vespasian, were of excellent quality, although their standard was slightly reduced—that is, from pure gold to standard 991. After the time of this emperor, the standard appears to have fallen to 938, and subsequently, about the time of Septimus Severus, it fell much lower. In the year 265 A.D. the gold coins were struck in a base alloy, containing—

827·3	of copper.
159·4	„ silver.
13·3	„ gold.
1000·0	

The silver of the Republic was always excellent, varying, according to Darcet, from 993 to 995, but under Imperial rule its debasement appears to have been rapidly effected, especially from the time of Nero until the third century, when the silver became mere *billon*, containing—

820	of copper.
160	„ lead and tin.
20	„ silver.
1000	

From the time of Diocletian, when the coinage of silver was resumed, it was of excellent quality. A series of Roman coins of the first three centuries,

[1] "La Monnaie dans l'Antiquité," Paris, 1878, t. i., p. 194.

[2] *Zeitschrift für Numismatik.* Band 1, p. 36, 1873. [3] *Op. cit.*, t. i., p. 187, *et seq.*

[4] This was the cementation process described by Geber in the eighth century, of which a full account is given by Biringuccio, original edition, p. 72 (1540).

found at Baden Baden in 1828, was analysed by Dr. Walchner, of Carlsruhe, whose results may be briefly stated as follows:—A coin of Heliogabalus proved to be the lowest standard (505), while one of Antoninus Pius, which contained 913 parts of silver, was the highest, coins of Commodus, Domitian, Hadrian, and Trajan varying from standard 797 to 890.[1] It may be added that there was a coin of the Triumvir Antoninus [2] (B.C. 31) which had almost the same composition as British silver coin, as it contained

925	of silver.
71	„ copper.
2	„ lead.
1	„ gold.
999	

Time will not permit me to trace the varying changes in the fineness of coins issued in the barbaric times which followed the overthrow of the Roman Empire. Judging from their appearance, the coins present endless variations of standard. In view, however, of the special interest connected with the early British series, I may point out that Mr. John Evans [3] has clearly traced the design they bear to the stater of Philip of Macedon, who struck the coin in question of gold of a high degree of purity. In view of this lecture, I have assayed an early British gold coin, believed to have been struck at a period ranging from 50 to 60 B.C.[4] Its design well exhibits the characteristic evidences of its descent, and it proved to contain

403·5	of gold.
400·2	„ silver.
196·3	„ copper (by difference).
1000·0	

The next historical point is presented by the early Saxon sceattæ, a single specimen of which, assayed by me, proved to contain 558 of silver, 12 of gold.

I have also assayed a silver coin of Burgred King of Mercia, 852-874, A.D., which proved to be of so low a standard as 331·6; and one of Ethelred (978-1016 A.D.), which contained 918·1 of silver, and a little gold, while a coin of Canute (1016 to 1035 A.D.) was of standard 931. Two coins of King Edward the Confessor, one of them kindly given me by Mr. John Evans, for the purpose of assay, proved to be of standard 943·2, and 940·4, both coins containing, in addition to the silver, nearly 2 parts of gold per 1,000.

With these slender links, I must pass to the series of coins which began with the Norman conquest, observing, however, that a further connection between the Roman, mediæval, and modern series is maintained by at least two coins, which were so widely circulated that they may almost claim to have afforded an international currency. These coins are the "bezant" of Constantinople, and the "florin" of Florence, which we know to have been of nearly pure gold.

"The gold bezants of the Greek Empire, and the gold coins struck during

[1] Quoted by Dr. Percy, "Metallurgy of Gold and Silver," part 1, p. 169, 1880.
[2] "Die Metallurgie Metallverarbeitung," Prof. A. Ledebur, p. 86, 1882.
[3] "The Coins of the Ancient Britons," p. 23. London, 1864.
[4] This coin is similar in design to that figured Plate C, No. 8 of the above work.

the ninth and tenth centuries by Arabic princes, in Sicily, were probably used, more or less, in mercantile transactions all over Europe, and are found occasionally in this country, but they had no legal currency here, and were probably accepted merely as bullion. In the middle of the thirteenth century, however, a native gold coinage was almost simultaneously adopted by the European nations. The first gold florin was issued by the Republic of Florence, in 1252. Louis IX. introduced gold coins into France, and the Emperor Frederick II. into his kingdom of Naples, and at the same time the same innovation took place in England." [1]

Taking the gold coinages first, the record begins at the year 1257, the forty-first year of King Henry III., who made a penny of the finest gold, which weighed two sterlings. This, as Ruding [2] points out, is remarkable as the first coinage of gold in the kingdom, and it is extraordinary that it took place at the height of the king's distress for want of money. The next step of importance was taken in 1343, when King Edward III. coined, or projected a coinage of the standard 994·8 (23 carats, 3½ grains, and ½ grain of alloy), which was referred to by later writers as the "old sterling" or "right standard" of England, and Lowndes, quoting the Red-book of the Exchequer, says that the ½ grain of alloy might be either of silver or copper.[3] Although these were not, as Stow considered, "the first coining of gold in England," the coins of Edward III. were of remarkable beauty, and it was asserted that they were struck from gold prepared by occult aid, by the well-known alchemist, Raymond Lully, who had a laboratory in the Tower of London. There are, however, chronological difficulties in the way of this explanation of the origin of the precious metal. No further change was made in the standard fineness of the gold coin until the year 1526, when King Henry VIII. reduced the standard to 916·66 (22 carats), the professed object of the reduction being to prevent the exportation of the coins to Flanders. The further debasement of the standard, which was effected in 1543-4, was preceded by a kind of scientific research, as the King ordered the Officers of the Mint to prepare, whenever they should be so directed by the Privy Council, alloys to the value of one pound in weight, of such fineness as should be devised by the said Council, in order that the general nature of alloys, similar to those used in foreign realms, might the sooner come to his Majesty's knowledge. The standard 916·66 (or 22 carats fine) (which is the standard of the alloy used at the present day for the gold coinage of this country) was again issued in 1544. By a subsequent indenture, dated 1545, the gold was brought down to 833·4 (20 carats fine).

King Edward VI. improved the fineness of the gold currency in 1549, and in 1552 an indenture was made authorising the coinage of gold both of the old standards 994·8 and of the standard 916·6. Queen Mary issued coins of fineness 944·8 (23 carats 3½ grains). Queen Elizabeth struck coins of both standards. The coinage of gold of the "old standard" 994·8 was abandoned in the twelfth year of King Charles I., and since that time the standard 916·6 (22 carats fine) has alone been issued. Coins made of the old standard

[1] "The Gold Coins of England," by R. L. Kenyon, p. 14, 1884.
[2] "Annals of the Coinage," vol. i., p. 10.
[3] Lowndes, "Essay for the Amendment of the Silver Coin," p. 18. London, 1695.

previously to that period continued to be current until the year 1732, when they were withdrawn from circulation by proclamation.[1]

The vicissitudes through which the silver coinage has passed have been greater than those that have affected gold. I have selected a few examples of coins issued before the Norman Conquest, and have assayed them. A coin of Burgred contained only 302 parts of silver in the thousand, while one of Ethelred was 918·4, and was probably intended to represent the old standard of England, 925. A coin of Canute proved to be of standard 931, which was clearly intended to represent the old standard. Two separate coins of King Edward the Confessor, assayed by me, proved to be 941, which is "better" than standard; but Mr. John Evans, who kindly gave me one of the coins, considers that this slight superiority to standard is due to the fact of copper having been removed from the surfaces of the coins by the operation of cleaning to which they had been submitted. Anglo-Saxon and Anglo-Norman coins are believed to have been of the "old standard," 925, and a coin of William the Conqueror which I assayed proved to be 922·8. In England, this old standard appears to have remained unchanged until the thirty-fourth year of King Henry VIII., when a great fall took place. A still more rapid fall in the standard fineness ensued in the rest of the reign of King Henry VIII., and in the reign of Edward VI. It fell to its lowest point in the fourth year of the latter monarch, when the pound of silver contained only 3 ozs. of fine silver and 9 ozs. of base metal—that is, the standard, expressed decimally, was only 250. Strangely enough, this base coinage was projected with a view to secure by the transaction the sum of £160,000, to be devoted to the restoration of the standard generally. Half this sum appears to have been actually obtained. As a step to the withdrawal of the base money, it was almost universally decried—that is, the coin which had been current at rates far above its intrinsic value was officially reduced to a value nearly corresponding with its standard of fineness. Dreadful distress was caused to the people, and the saddest pictures are drawn of the financial condition of England at the time In 1552, the standard was restored to nearly its original richness, as coins containing 11 ozs. 1 dwt. of pure metal and 19 dwts. of base metal, or standard 921, were issued, and this alloy was maintained by Queen Mary. The accession of Queen Elizabeth contributed to the restoration and maintenance of the standard fineness of the coin. A proclamation, dated September 27, 1560, stated that "her Majesty, who, since she came to the throne, never gained anything by the coinage, nor yet ever coined any manner of base monies, for this realm, had begun a coinage of fine money in the Tower of London." Notwithstanding the Queen's efforts to restore the coinage in England, the coins circulated in Ireland were deplorably low, as the pound only contained 2 ozs. 18 dwts. of fine silver, and 9 ozs. 2 dwts. of copper (that is, the standard was only 250). Well might that shrewd economist, William Stafford,[2] remind her Majesty that, "though gold and silver be the mettals comonly wherin the coyne is strycken to be the tokens for exchange of things between man and man, yet it is the wares necessary for man's use, that are exchanged in deede under the outward name of the coyne;" or, in other words, by diminishing the value of coin, its purchasing power is diminished.

[1] Lord Liverpool's letter to the King, p. 32. Edition published by the Bank of England, 1880. [2] "A Brief Conceipt of English Policie," p. 29. London, 1581.

The restoration of the standard of the silver, begun in the reign of King Edward VI., was, however, completed by Queen Elizabeth, and it has not been since debased.

Before leaving this part of the subject, it may be well to offer a few remarks on the debasement of coinage generally. The famous antiquary, Sir Robert Cotton, in a well-known speech made before the Privy Council in the reign of Charles II., observes, "what renown is left to Edward I. in amending the standard, both in purity and weight, . . . must strike as a blemish upon princes that do the contrary. When Henry VIII. had gained us much of power and glory abroad, and of love and obedience at home, as ever any, he suffered shipwrack of all upon this rock." And he elsewhere points out "that every man will rate his commodity in sale, not according to the accompt of pence or pounds, but to the weight of pure silver contained in the current money."

With reference to the apparent motives for the debasement of the currency, Lord Liverpool observes that "these motives were, first, a desire of augmenting the royal revenue, and, second, principles of mistaken policy," supported by "an idea that they should thereby prevent the coin from being exported," and he adds, "but this idea has been fully exploded since the principles of commerce and foreign exchanges have been well understood." [1] It may be pointed out that the exact standard fineness of the alloy used is a matter of but small importance, and that a coin poor in precious metal is not really "debased," if it is not made current at a rate below its intrinsic value.

One other method of debasing the coinage remains to be noticed, which was, so far as I know, confined to Roman times. It consists in the issue of pieces of copper, iron, lead, or tin, plated with a thin layer of silver, or more rarely gold. The workmanship of such coins exhibited much skill and care, and they appear to have been issued simultaneously with coins of full value, often with a view to defray the cost of the coinage of the good pieces. An elaborate literature has been devoted to them, which has been well condensed by M. Lenormant.[2]

The issue of coins of base metal by King James II., for use in Ireland, can hardly be called a depreciation of the standard, as in many cases they contained no silver at all, but were made from old guns, bells, kitchen utensils, "and the refuse of metals molten down together, and valued, by the workmen in the Mint, at no more than three or four pence the pound weight; but when coined into sixpenny, shilling, or half-crown pieces, and made current by arbitrary power, it passed at the rate of five pounds sterling the pound weight, or eleven thousand two hundred pounds the ton, when at the real value—namely, fourpence the pound weight—the compound metal was not worth more than thirty-seven pounds six and eightpence the ton." [3]

I have thus attempted to trace the history of the gold alloy of standard fineness 916·6, and the silver one of 925, the alloys used in this country for the gold and silver currency, and as the gold represents a large proportion of the coinage of the world, it may fairly claim to be the most important gold alloy in existence. England is not the only country in which it is retained; the explanation of its existence in other countries is found in the fact that

[1] *Op. cit.*, p. 123. [2] *Op. cit.*, t. i., p. 221, *et seq.*

[3] King's state of the Protestants in Ireland, quoted in an essay on Irish coins by James Simon, F.R.S., p. 62. Dublin, 1749.

standard 916·6 is the metric equivalent of 22 carat gold, and, as the carat system has been in use from early times, it is natural that many nations should have originally adopted the convenient proportion presented by $\frac{22}{24}$, or $\frac{11}{12}$, which this alloy represents, and it has, accordingly, held its own in British India, Russia, the Turkish Empire, Portugal, Persia, and with a slight variation in Brazil.

As it will not be possible to examine the history of the alloys at length, attention must be limited to the more important ones, of which the alloy containing 900 parts of gold in the 1,000 parts demands special notice.

The coins in circulation in France from the beginning of the seventeenth to the end of the eighteenth century varied in fineness from 900 to 982; for instance, the louis d'or of King Louis XIII. were 22 carats fine, the ecus d'or of Louis XIV. were 23 carats, while the lys d'or of the same monarch were 23 carats and one-fourth of a grain.[1]

When, however, the decimal system of weights and measures was fairly established, coins were issued in conformity with it. The law of the 28th Thermidor, An. III. (1796), fixed the franc as the monetary unit, and enacted that the standard fineness of the silver coins should be 900, the weights as well as the fineness of the coins being strictly in accordance with the decimal system, although round numbers were not secured in the respective weights of the coin. Eight years later, the law of the 7th Germinal, An. XI. (28th March, 1803), prescribed the coinage of gold pieces of 20 francs, the standard of which was also 900. A subsequent law, the result of the recommendations of a committee appointed by the French Senate, directed, on the 25th of May, 1864, that pieces of 50 and 20 centimes should be of standard 835; and on the 14th of July, 1866, the standard of fineness of pieces of one and two francs was also reduced to 835.[2] By the Monetary Convention of the 23rd December, 1865, concluded between France, Belgium, Italy, and Switzerland, the standards of fineness above described were adhered to. Several other countries, notably Roumania, Servia, Greece, Scandinavia, and most of the republics of South America, have partially adopted the same monetary system. In Germany, in virtue of the laws of the 4th of December, 1871, and the 9th of July, 1873, the standard fineness of both gold and silver has been fixed at 900. In the United States of America the use of the alloy 900 fine has been confirmed, for both gold and silver, by the Coinage Act of the 12th of February, 1873. It will be evident, from the foregoing remarks, that the two really important alloys used for coinage of gold have respectively the standard fineness 916·6 and 900, while for silver coins the standard 900 is now more widely used than any other, England alone employing 925, which still maintains the connection with Saxon coins.

In concluding this portion of the subject, it will be sufficient to examine briefly a few other standards of fineness, which either may be actually struck at the present time, or the circulation of which is permitted by the legal enactments of certain countries.[3] First, as regards gold, the richest gold

[1] Much information of interest relative to the standard fineness of coins of the seventeenth and eighteenth centuries will be found in the "Traité des Monnaies d'or et d'argent, examinées sur les rapports du poids, du titre, et de la valeur réelle," par P. F. Bonneville. Paris, 1806. [2] "Annuaire publié par le Bureau des Longitudes," 1884, p. 292, *et seq.*

[3] An excellent classification of the alloys used in different countries will be found in "La Question Monétaire," par M. H. Costes, Paris, 1884.

alloy which survives to the present day would appear to be the gold ducat of the Austro-Hungarian Empire, which, in accordance with the laws of the 24th December, 1867, and the 9th of March, 1870, contain no less than 986 parts of fine gold in 1,000. The issue of gold ducats of fineness 983 is permitted in the Netherlands, by laws of 26th November, 1847, and 6th June, 1875. The poorest gold alloy in circulation appears to be that employed for certain Egyptian coins, the standard of which is only 875, and the same standard is also used for gold coins in Mexico, and in the Philippine Islands.

In the case of silver, the variations are greater. Since 1868, Austro-Hungary has issued kreutzers which contain, respectively, 400 and 500 parts of fine silver in 1,000. The 10 öre piece of Norway also contained only 400 parts of fine silver. The standard of the silver coins of Brazil is 917; the silver coins of British India are 916·6. In Russia, the roubles are of standard 868, while that of the Turkish piastre is 830. In the Netherlands the standard 945 for pieces of ½ to 2½ florins, which is the richest alloy of silver actually in circulation, is employed; and the standard 720 is employed for the currency of Java, because it is the most homogeneous of all the silver-copper alloys.[1]

The alloys to which reference has hitherto been made have been simple ones of two metals. In the case of gold coins, the second metal contemplated by law was copper, but silver was, in many cases, used, either to the exclusion of copper, or in conjunction with it. The Australian gold coins first issued contained a considerable proportion of silver, as their colour showed, but in all the examples given the use of triple alloys has rather been the result of accident than of design. It will now be necessary to consider triple or complex alloys at some length. In early times, when complex ores were treated by metallurgists who may have possessed considerable skill, without knowing how to insulate each of the metals present in the ore, singular admixtures have been obtained as the result of the operation. A very experienced copper smelter, Mr. Tyrell, of Swansea, has shown[2] that it is only necessary to smelt copper pyrites with a small addition of an ore which contains tin, in order to obtain bronze of the composition frequently met with in ancient implements or weapons. Numerous instances of the involuntary use of complex alloys for coinage might be given, but the best example is probably presented by the coins of the early Britons, which were of copper alloyed with 20 to 25 per cent. of zinc and 5 to 11 per cent. of silver, together with small quantities of gold, lead, and tin. Mr. John Evans has pointed out that the Saxon stycas range through a wide field of alloys, and may in some cases have been formed by melting together the coins discovered in "hoards" of Roman coins with, of course, very variable results.[3] In the case of gold, such triple alloys have been used but seldom. A modern instance in which their use was suggested is presented by the triple alloys of gold, copper, and zinc, prepared in 1873, by M. Péligot.[4] He showed that an alloy containing 58·1 per cent. of gold, 36·1 of copper, and 5·8 of zinc is of good colour, can be readily worked, and possesses the advantage of being decimal as to weight. Péligot also suggested

[1] Levol, *Ann. Chim. et Phys.* (3) t. xxxvi.; Roberts, *Proc. Roy. Soc.*, vol. xxiii., p. 481, 1875.

[2] Paper published by the Swansea Scientific Society. Session 1880-1.

[3] Presidential Address, Numismatic Society, 1880, and *Numismatic Chronicle* (3), vol. iii., p. 26.

[4] *Comptes Rendus*, t. lxxvi., p. 1441.

the use of three alloys of silver, copper, and zinc, containing respectively 5, 10, and 7·2 per cent. of zinc, and 90, 80, and 83·5 per cent. of silver, the rest being, in each case, copper; and he also described three simple alloys of silver and zinc, containing respectively 5, 10, and 20 per cent. of zinc.[1] I have prepared several of the alloys, and entirely confirm his observations respecting them. The alloy of standard 900, used in France, when melted with 78 grammes of zinc per kilogramme, yields an alloy containing

83·5	of silver.
9·3	„ copper.
7·2	„ zinc.
100·0	

which is whiter and more malleable than the alloy which is used for the subsidiary coins. Certain coins struck at Alexandria, in the third century,[2] contained

91·38	of copper.
3·85	„ tin and traces of lead.
2·89	„ zinc.
1·81	„ silver.
99·93	

The Japanese employ, for the purposes of ornament or currency, several such alloys. The Nebus, now withdrawn from circulation, contained 22·75 per cent. of gold, 76·00 of silver, and 1·25 of copper, and I am informed by Mr. Tookey, who was formerly assayer in the Imperial Mint at Osaka, that the composition of these coins was extremely uniform. It is to be regretted that they were extensively and successfully counterfeited by western visitants to Japan, in an alloy which contained, when melted, only 0·47 per cent. of gold.

Triple alloys, in which silver is the main constituent, have often been used. A singular alloy of silver, copper, and zinc has been extensively employed in Switzerland for the manufacture of subsidiary coins. A very low alloy of silver and copper has long been employed for coins of small value; such an alloy is called *billon*, and was formerly widely adopted on the Continent generally in modern as well as ancient times. The precious metal contained in the mass is not present in sufficient quantity to give the alloy the colour of silver, and, therefore, the copper is removed by the action of a solvent from the surface of the "blanks" before they are coined, but this layer of silver soon wears off when in circulation, and the coins assume the normal tint of the alloy from which they are made.

The advantage of employing precious metal in this way consists in the possibility of striking subsidiary coins of some value, but of comparatively small weight; the objections to the use of such metal are numerous, and were well expressed in 1790 by M. Gabriel de Cussy,[3] who pointed out that the manufacture of such coins was expensive, that when withdrawn from circulation they are very difficult to refine, and, finally, they may very easily be counterfeited in alloys which contain no precious metal whatever. Much

[1] *Loc. cit.*, p. 645, 1864. [2] Lenormant, *loc. cit.*, t. i., p. 205.
[3] *Rapport au Comité des Finances*, Paris, 1790.

force was imparted to this latter objection by the statement that one-third of the *billon* then in circulation in France was either of foreign origin or spurious. The use of such coins of *billon* still lingers in Europe, but, as M. Mirabeau said, in a speech delivered before the National Assembly of France in 1790, to which I have already referred, this "detestable money" should be abolished, if only because "a false coiner, with less than 20 sols, can counterfeit 12 livres at a profit of 1,100 per cent." [1] The base alloy he had in view contained only one-sixth of its weight of silver, the rest being copper. He appears, however, to have advocated the use of an alloy of about equal parts of silver and copper, and pieces of 15 and 30 sous, of standard fineness 667, were struck in 1791.

The alloy next in importance to those we have hitherto considered is bronze, which, as has already been stated, played an important part in ancient currency. Its modern use on an extended scale is due to the Government of the late Emperor of the French, Napoleon III., by whose direction the old sous circulating in France afforded the basis for a triple alloy, containing 95 parts of copper, 4 of tin, and 1 of zinc, the weights of the respective coins of one to ten centimes being a gramme for each centime. The law regulating this coinage was passed by the Assembly in May, 1852, and the issue of bronze from that time up to the year 1868 amounted to no less than 59,300,000 francs. All the facts connected with this coinage have been elaborately described by M. Ernest Dumas in a valuable work to which I have before had occasion to refer.[2] It is an extremely durable alloy, as will be shown in the fourth lecture. Its coinage was undertaken in England in 1861, by the advice of the late Prof. Graham, Master of the Mint, and the amount of bronze coin now in circulation is estimated to be about 3,000 tons.[3]

Brass was extensively used by the Romans for subsidiary coins, and, in fact, silver does not appear to have been employed until "the first Punic War, 269 B.C." [4]

Savot mentions the use of a triple alloy of copper, zinc, lead, and a small quantity of tin, to which the name of *potin* was given; and Lenormant states [5] that it was only used for money by certain tribes of Gaul, between the wars of Cæsar and the organisation of the Gaulish provinces by Augustus. The coins were always cast, and prove, on analysis, to contain

60	of copper.
20	„ lead.
10	„ zinc.
10	„ tin.
100	

The use of nickel is extremely ancient. Dr. Walter Flight, F.R.S., has

[1] "Collection Complette des Travaux de M. Mirabeau, l'ainé a l'Assemblée Nationale," t. v., pp. 25, 81. Paris, 1792.

[2] "Notes dur l'émission en France des Monnaies décimales de bronze." Paris, 1868.

[3] In recent years very large quantities of bronze coins have been issued, the amount in 1912 being 744 tons, representing 93 million pieces, having a nominal value of £323,235.

[4] Sir John Lubbock, *Nineteenth Century*, p. 797, November, 1879.

[5] Lenormant, *loc. cit.*, t. i., p. 205.

shown[1] that coins of the second century B.C. were struck in an alloy containing

77·585	of copper.
20·038	„ nickel.
0·544	„ cobalt.
1·048	„ iron.
0·038	„ tin.
trace	„ silver.
0·090	„ sulphur.
99·343	

Pence and half-pence, to the value of £3,000, were coined at the Mint, in the years 1869-71, for use in the Colony of Jamaica, of an alloy containing

75	of copper.
25	„ nickel.
100	

but when a further coinage of nickel of the nominal value of £500 was required, Mr. Fremantle reported that the charge to the colony of Jamaica for the metal alone "would exceed the nominal value of the coin,"[2] a fact which points to the difficulty of determining the weight that may be safely given to the individual pieces of a token coinage when the metal employed is liable to serious fluctuations in commercial value.[3] Pieces of 5 and 10 centimes of the same alloy have long been in circulation in Belgium. In Germany also, the pfennige are of this alloy, and it is also employed for the subsidiary coinage of Brazil. Certain American nickel coins contain 12 per cent. of nickel and 88 of copper. The important contributions of Herr Fleitmann to the metallurgy of nickel have rendered it possible to use the pure metal for coinage, and the 20 rappen pieces of Switzerland are now struck in nickel without alloy.

The claims of platinum to be used for coinage did not escape M. Rochon,[4] and the fact is remarkable, considering how comparatively rare the metal was when he wrote in 1786.

With regard to metals which have not as yet been employed for coinage, I would direct your attention to those very light specimen coins of pure aluminium, and of aluminium alloyed with 2 per cent. of nickel, for which I am indebted to the distinguished metallurgist, Mr. G. Matthey, F.R.S.

The points with which we started were, you will remember, that the base metal added to a precious one may be viewed, first, as a useful constituent of an alloy, and, second, as a source of gain. I trust it will have been evident that within certain limits the standard selected for the alloy is not a matter

[1] *Numismatic Chronicle*, p. 305, 1868.

[2] Fourth Annual Report of the Deputy Master of the Mint, p. 11, 1873.

[3] Aluminium coins were struck in 1907 for East Africa, Uganda, and Nigeria, but were discontinued in the following year (1908), as they were found to be unsuitable for such tropical climates. These low denominations were replaced by nickel-bronze coins of similar size (*39th Mint Report*, 1908, p. 13). The cheapening of nickel in recent years has made it possible to make further use of it for coinage purposes. Since 1907 large quantities of nickel-bronze coins have been struck at the Royal Mint for East Africa, Uganda and Nigeria.

[4] *Loc. cit.*, pp. 17 and 45.

of much importance, provided the base metal be added to precious metal in such proportions as to combine the maximum convenience with the best physical properties.

Viewed as a source of gain, it must be borne in mind that "any person" has the right to coin gold, provided the actual manipulation of the precious metal is entrusted to the officers of the Mint, and, as has been well remarked by M. Dalsème, of all its ancient rights the governing body in the State alone preserves the privilege of issuing coins, the intrinsic value of which is slightly less than the value at which they are current, and this right is guarded by law, and exercised in the public interest. In the next lecture I will attempt to show what precautions are taken to secure accuracy in weight and fineness of the coinage, more especially in the case of the sovereign, which is so widely circulated, and the integrity of which is so implicitly trusted that it may be said to epitomise the financial honour of the nation.

[*To face page* 47.

Research Laboratory, Royal Mint
(Pyrometer and Micrographic Plant).

ALLOYS USED FOR COINAGE.

THIRD LECTURE.[1]

In the last lecture we considered the changes through which the standard fineness of alloys used for coinage have passed in this country since the Norman conquest, and we saw that at a critical period of our numismatic history the silver coins contained only a quarter of their weight of precious metal, and, therefore, fully justified Latimer's attribution, "Your silver has become dross."

The questions we have now to deal with relate to no violent changes, and do not comprise the history of either national disaster or national success; but they have a certain importance of their own, as they refer to the methods by which standard fineness can be recognised and maintained.

The want of a method for ascertaining the degree of purity of gold and silver, or for determining the amount of precious metals present in their alloys, must have been felt as soon as the use of metals for currency was established. The history of assaying has yet to be written, but in rapidly reviewing the methods of assay which have been practised or proposed, it will be well to consider them in an order that is in the main chronological, but which enables the physical methods, as distinguished from the chemical, to be dealt with first.

The nation for which the honour of striking the first coins is claimed gave its name to the "Lydian stone," or, as it is called in more recent times, the "touchstone." It is a dark basaltic rock, of fine texture, upon which a fragment of precious metal readily leaves a streak when drawn over its surface. The comparison of the streak left by the gold to be tested with similar traces derived from alloys of known standard and composition, afforded a ready means of ascertaining, approximately, the fineness of the metal under examination; while further insight into the character of the alloy was gained by submitting the streaks to the solvent action of an acid. There is an abundant literature [2] showing the degree of accuracy that may be attained by means of this stone; its use has survived for approximate assays until the present day.

Then, again, there was the method of ascertaining the purity of metals by their density, as compared with that of water, devised by Archimedes, B.C. 212, which is applicable to both gold and silver, and is still often resorted to when the metal to be examined must be preserved intact. The usefulness of density, as affording a trustworthy indication of standard fineness, has often been pointed out, notably by W. Symonds,[3] in 1756, and more recently by Dr. O. Broch.[4]

The possibility of ascertaining the standard fineness of alloys by the aid of electricity long ago occupied the attention of physicists. In 1823, Becquerel[5] suggested that trustworthy indications might be afforded by the electromotive

[1] *Journ. Soc. of Arts*, 1884, vol. xxxii., p. 881.

[2] "De re Metallica," by George Agricola. Lazarus Erckern's work, translated by Sir John Pettus, 1683, chap. ix., p. 130.

[3] Essay on the weighing of gold, etc. London, 1756.

[4] *Norwegian Nyt. Mag. fur Naturvsk*, Christiania, 1876.

[5] *Ann. de Chim. et de Phys.*, vol. xxiv., p. 343.

force developed when the alloy to be tested is placed in an exciting fluid together with an alloy of known composition. The subject was partially investigated by Oersted,[1] in 1828, and its practical importance was further pointed out by Gay-Lussac,[2] in 1830. In 1878, the use of magnetic induction for indicating the composition of alloys was suggested by Professor Hughes,[3] who showed incidentally that the induction balance affords a ready means for detecting counterfeits, and I have elsewhere pointed out the degree of accuracy of which this instrument is susceptible.[4] The method which involves the use of the spectroscope also deserves mention here, although it is, as yet, more delicate than trustworthy.[5]

These physical methods, both ancient and modern, are open to the objection that the uncertainty of the results they afford increases with the complexity of the alloys under examination; and further, the indications are complicated by changes in the physical state of the metals, produced either by hammering or annealing.

Pliny states that in his time a method was in use for estimating the amount of silver in an alloy of silver and copper, by the degree of discolouration or blackening which attends the heating of the alloy in air. This method, long practised in France, and known by the name of *essais à la raclure* (scrapings), or *à l'échoppe*, is described by Rochon,[6] who says that it was generally recognised in the Roman mints in the time of Marius Gratidianus, triumvir of the money, and later by Chaudet,[7] who gives a table showing that silver of the English standard (925), when heated to low redness in a muffle, becomes uniformly grey-white, while intermediate tints are produced by heating lower alloys, until the standard used for the French subsidiary coinage (835) is reached. As this becomes quite black under the treatment, the process ceases to be useful for alloys of lower standard.

In very early times the need must have been felt of some chemical method of isolating the precious metals—of separating them—that is, from their base associates—so that the gold or silver, when purified, could be weighed, and the amount originally present in the mass deduced by calculation.

The crude method of assay, already described, which depends on the change of colour produced by oxidation of the baser constituent of an alloy, leads up to the method used from very early times, which also depends on the principle that precious metals will resist oxidation, while the metals with which they are usually associated will not.

Its main outlines may be indicated as follows:—When lead is melted with free access of air, a readily fusible substance forms upon its surface. This substance may be allowed to flow away, or, if the metal is contained in a suitable porous receptacle, called a cupel, the fusible oxide sinks into this containing vessel; in either case the oxidation of the lead affords a means of separating it from precious or inoxidisable metals, if any be originally present in the lead. I found lead in the ancient ornaments both of gold and

[1] *Ibid.*, vol. xxxix., p. 274.
[2] Instruction sur l'Essai des Matières d'Argent par la voie Humide.
[3] *Proc. Roy. Soc.*, vol. xxix., p. 56.
[4] *Ibid.*, and *Phil. Mag.*, (5), vol. viii., p. 50. Tenth Ann. Report of the Mint, p. 46 1879.
[5] *Phil. Trans. Royal Society*, vol. clxiv., p. 495. 1874.
[6] "Essais sur les Monnoies," p. 17. 1792.
[7] "L'Art de l'Essayeur," p. 77. Paris, 1835.

silver, which Dr. Schliemann permitted me to analyse, and Pliny teaches that the Roman metallurgist used lead for the purification of gold and silver, for he says, "excoqui non potest, nisi cum plumbo nigro aut cum vena plumbi." The greatest of the early alchemists, Geber, who died in A.D. 777, knew perfectly that the lead "acquired a new weight" when heated in air, and I have elsewhere [1] tried to show how important the recognition of this fact was to the whole fabric of modern chemistry; it is not a little interesting that, among the very first experiments recorded by our own Royal Society, is a metallurgical series relating to the weight of lead increased in the fire on the "copels" at the assay office in the Tower, the account being brought in by Lord Brouncker, in February, 1661.[2]

The interest of the art of assaying, from a purely scientific point of view, was generally admitted in the seventeenth century. Lazarus Erckern, for instance, described it as "the very inlet and mother of many other honourable and profitable sciences," while William Badrock,[3] apparently regarding the art as an element of general culture, pleads its claims to be studied by "all gentlemen"

Having shown the great amount of interest attached to the subjects, I will now return to the actual practice of the art as a metallurgical operation.

Geber, the Arabian, gives, if mediæval translations of his works are to be trusted,[4] a sufficiently accurate description of the process to enable it to be conducted at the present day with no other aid than his; but it must be remembered that it was the object of the alchemist to distinguish silver from gold, and to isolate the metals, rather than to determine the amount of one metal present in admixture with another. Geber calls the process of cupellation the trial of the *cineritium*, and he points out, in the course of a description that deserves to be reproduced here, that "there are two bodies perfect, abiding the trial, to wit, *sol* (gold), and *luna* (silver). Take," he says, "sifted ashes or calx, or powder of bones of animals calcined . . . moistened with water, and make the mixture firm and solid with your hands, and, in the midst of it, worked into a round flattish lump, make a round and smooth hollowness, and upon the bottom of it strew a small quantity of glass beaten to powder, which lay to dry. When dry, put your metal into the hollowness thereof, which you would try to prove, put coals of fire upon it, then blow with bellows upon the surface till the metal flows; upon which, being in flux, cast part after part of lead, and blow with a flame of strong ignition." This is to be continued "until the lead is vanished," and precious metal is left "still or quiet, and you see it clean and clear in its superficies"—that is, the lead has dissolved the oxides of the base metals, and has carried them into the cupel, leaving the gold or silver, or an alloy of both, in the form of a button on the cupel.

This operation, as described by Geber, would more nearly correspond to a refining operation conducted on a large scale, with a view to the extraction of silver from lead, rather than to the method of assay as practised at the present day on a few grains of metal.

[1] Introductory Lecture to the course of Metallurgy at the Royal School of Mines, Session 1880-81. [2] MS. Register Book of the Royal Society.

[3] Author of a "New Touchstone for Gold and Silver Wares," p. 31. London, 1679.

[4] There is a good English edition of the Seventeenth Century, "The Works of Geber," translated by R. Russell. 1686.

The method of conducting assays, on what would at the present day be considered to be a very large sample of metal, seems to have been held to be necessary in the twelfth century, for in the official trials of the coin in the time of King Henry II., 1154-89, the "Miles Argentarius" and the "Fusor"[1] are instructed to take before the Barons of the Exchequer a pound of "twenty solidi" of the coin, which they are to place on a "*vasculum ignitorum cinerum quod in fornace est.*" The metal resulting from the trial is then weighed, and the amount it has lost is noted, and, if it is considered that the result of the trial is inaccurate, or "too much metal has been lost, say by the boiling, or by being carried off in the lead" (*illud quasi plus justo consumptum fuerit ignis scilicet exæstuatione vel plumbi infusione*), then it is to be repeated.

The amount of metal which has, for at least two centuries, been taken for assay is 12 grains troy, and this weight, which is known as the "assayer's pound," has the same number of divisions as the troy pound; the fineness of any given weight of metal is, therefore, indicated by the results of an assay, without tedious calculation. It has been shown that the process was officially recognised in this country in the reign of Henry II., and in France the first official mention of it occurs about the year 1314. It is the only method of assaying silver practised at the present day (1884) at the English Mint, although another method is used for verifying the composition of its alloys.

With regard to the apparatus required:—In Geber's work "of furnaces" there is no mention or illustration of the "muffle" furnace, so that he seems to have conducted the process in a cupel surrounded by incandescent fuel.

Biringuccio (1540) gives illustrations and detailed descriptions of appliances which hardly differ from those now in use, and so does his contemporary, Agricola.[2] Budelius[3] (1591) gives a drawing of a furnace which somewhat resembles the type still used in continental mints, except that the muffle, or oven, is placed close to the base of the furnace; and the "Sculptures" of Sir John Pettus, reproduced from the works of Lazarus Erckern,[4] show various forms of muffles and furnaces, some used by the ancient assayers, others adopted in the middle of the seventeenth century at Nuremberg, where the goldsmiths flourished so vigorously. He also gives an improved form of furnace, "made of armour plates," closely corresponding in its general arrangement with a furnace now lent by the Mint to the science collection at South Kensington, which is specially interesting, as tradition points to it as being the furnace used by Sir Isaac Newton in his experiments on cupellation when Master of the Mint. Several transitional forms of furnace between the old one just mentioned and those now used by the Mint[5] are still preserved in the Assay Office. The tongs and other tools incidentally used do not require special notice, as the changes that have from time to time been made

[1] Quoted by Lowndes, "Essay for the Amendment of the Silver Coins," p. 155 (London, 1695), from the Black Book of the Exchequer, written in the time of Henry II., cap. 21, Officium Milites Argentarii et Fusoris.

[2] "De re Metallica."

[3] "De Monetis et Re Numaria, Coloniæ Agripp." 1591.

[4] *Op. cit.*, p. 17.

[5] A drawing of the modern furnace was prepared for Dr. Percy's work, "Silver and Gold." Part I., p. 256. 1880.

in them have only rendered their forms more delicate and handy, and have hardly altered their general type.

With regard to the balances employed, it may be sufficient to point out that, for centuries, they have been constructed with great delicacy, and that they now turn with $\frac{2}{1000}$ grain, when loaded with 10 grains. In fact, the use of the balance in very early times, for the purpose of assay, absolutely demolishes the claim of quantitative chemistry to be considered of comparatively modern origin. The indications afforded by the balance as to the result of an assay are not absolute, as the process is liable to error from several sources, and needs to be controlled in the manner which will be described subsequently.

The point to bear in mind at this moment is, that if the silver has been associated only with readily oxidisable metals, especially copper, as is usually the case when silver coins are assayed, then it only becomes a question of providing the amount of lead necessary to furnish, by oxidation, sufficient litharge to dissolve the oxides and carry them away. If, however, the silver is associated with gold, the latter metal resists oxidation, and will remain on the cupel with the silver, for—again to quote Geber—it will in "no wise forsake it." The cupellation stage must then be supplemented by a "parting" operation—that is, the silver must be dissolved away by some solvent which will leave the gold untouched, and for this purpose nitric acid is universally employed. If the silver contains but a minute quantity of gold, the presence of the latter will be indicated by a few specks of brown powder left at the bottom of the vessel in which the silver is dissolved; if, however, the silver contains about one-third of its mass of gold, and has been extended into a strip, the gold will remain after the action of the acid as a coherent band, retaining the original form of the strip, but much reduced in volume. This action of nitric acid on an alloy of gold and silver was certainly known to Geber and the early alchemists; but the first official mention of the use of the parting assay appears to be in a decree of Philippe de Valois,[1] in the year 1343, confirming its use in the French Mint. The assay methods for silver and gold are analogous, in so far that both are purified by the action of a solvent; but the base metals are removed from silver by fused litharge, while in its turn silver is parted from gold by nitric acid. There is, then, this difference between the assay of gold and silver. In the case of the cupellation assay of silver the button of metal has only to be removed from the cupel, and when the adhering bone-ash has been removed by a brush it passes direct to the balance.[2] The process would also be sufficient for gold if it contained no other precious metal; when, however, the problem is to ascertain by assay how much gold is contained in an alloy, which may contain silver, or platinum and other metals of similar properties, then care must be taken that the amount of gold believed to be present in the alloy does not exceed the one-third part of the mass, as a larger proportion of gold would protect the alloy from the solvent action of the acid, and the greater the amount of gold the less perfect would be the attack of the acid.

In any case the first stage of assaying a gold alloy, say a sovereign, is to

[1] Boizard, "Traite des Monnoies," p. 176. 1692.

[2] This process for assaying silver has now been superseded by the Gay-Lussac or volumetric method.

melt a portion of it with such an amount of silver as shall yield a button containing rather less than one-third of its weight of gold.

For the sake of convenience, and for the incidental advantage that the solvent action of fused litharge removes copper and other impurities, the first stage of the assay of gold is conducted on a cupel, the object to be attained being mainly to secure a button of gold and silver in a convenient form for submitting to the subsequent operations. The alloying stage would, however, be just as effective if it were conducted in a small non-porous receptacle, such as a small crucible of glazed porcelain.

The subsequent operations are flattening the button, annealing it, rolling it into a strip, and annealing it a second time. It is then coiled into a spiral, or cornet, and treated by two successive portions of nitric acid, in order to remove the silver; after this the spiral of spongy gold, which retains the original form given to the silver-gold alloy, is heated to redness, when it becomes bright, and is sometimes so coherent that it may be unrolled without fracture.

This is an outline of the processes of assaying: the precautions which are adopted with a view to secure accuracy remain to be considered. Inaccuracy in silver assaying mainly arises from loss of silver, which may disappear in small but variable quantities, either by volatilisation or by sinking into the cupel with the litharge. The amount of metal lost varies with the temperature, which is never uniform throughout the muffle; and the results of assays, as indicated by the balance, have, therefore, to be controlled by assays on pieces of metal of known standard, distributed in such a way as to represent the varying degrees of temperature throughout the muffle. The metal lost by any given check-piece is added to the assays in close proximity to it, and, as the amount of metal lost very often amounts to $1\frac{3}{4}$ per cent., the apportioning of the additions to be made demands great skill on the part of the assayer, who has also to decide from the appearance of the buttons whether they have retained lead or not, in which case they would, of course, be unduly heavy.[1] In gold assaying, on the other hand, although, as Geber knew, gold resists the action of molten litharge better than silver does, some precious metal may be lost either by volatilisation or by retention in the cupel; but the chief sources of error are (1st), solution of gold in the acid used, which would reduce the weight of the cornets, and (2nd), retention of silver by the cornets; but these inverse causes of error may be combined without neutralising each other. Some means of checking the results must, therefore, be provided, and it would appear that for centuries implicit confidence has not been placed in the indications afforded solely by the assays, as comparisons have invariably been instituted between the pieces of metal taken for assays and standard trial plates, or pieces of known composition, assayed side by side with the coins, so that any error affecting the coin assays also affects the check-pieces, and, therefore, the error can be allowed for.

The trial plates by which silver and gold coin have been tested possess, it seems to me, an amount of interest that can hardly be over-rated (see also p. 69). The oldest of them to which a date can be assigned is a silver plate, imperfectly impressed with the dies of a coin of the time of Henry III. (1216-

[1] This process for assaying silver has now been superseded by the Gay-Lussac or volumetric method.

1272). A silver plate is alluded to as follows, in the *Rotulus de Moneta*, of the seventh and eighth years of King Edward I. :—" Premerement qe hom doit fere un estandart, qe doit demorer al Escheker, ou en quel lieu qe nostre seignor le Roy vodra " ; and in 1326 there is a record of the provision of two silver plates for testing the silver coined by King Edward II. for the Duchy of Aquitaine, " one plate to be of the just weight before the fire, and the other such as it (the metal tested) ought to be after the assays." [1] This is interesting, because it seems to point to the fact that the amount of silver which should be " lost in the fire " had been experimentally determined at that early period. Many of the old trial plates were formerly kept in the Pyx Chapel Abbey, Westminster Abbey (see Plate IV.), almost the only relic which remains of the church built by Edward the Confessor ; and on the altar tomb believed to be that of Hugolin, the first Chancellor of the Exchequer, there is a circular dish-shaped cavity on which a small furnace may have rested, if,[2] as is probable, the trial of the pyx was at one time conducted in this building. The trial plates were removed in 1842 from the Pyx Chapel to the office of the Queen's Assay Master in the Mint ; and I am fortunate in being able to offer to the Society photographs of some of the more interesting of these. The trial plates were always divided into several portions, and, like the old Exchequer " tallies," this division was effected in rough serrations, so that portions of the original plate entrusted to the different officers could be readily identified. Of those which are photographed (see Plate IV.) the more interesting are probably No. 1, made in the 17th year of King Edward IV. (1477), and No. 4, which marks the adoption of the standard now in use, 916·6, by King Charles II. in 1660. All the plates, however, possess peculiar interest, for in relation to the assays of the " alloys used for coinage," they are the signs of centuries of responsibilities, which I am fully sensible it is a privilege to be permitted to sustain.

An examination of a series of assays made of the trial plates shows that, although the standards of fineness were always prescribed by law, the plates have, nevertheless, at times been very inaccurate.

The imperfections of the gold plates are mainly due to sources of error which had been recognised, but which were ignored when the last plates were made ; and it is well to explain, therefore, that plates were in former times authoritatively pronounced to be " standard " simply with reference to the results of an inaccurate process of assay. One process consisted in submitting an accurately weighed portion of the alloy to a rapid method of chemical analysis, whereby impurities are eliminated, and the precious metal thus purified is again weighed, but the method is complicated, and the accuracy of the result may be affected by the retention of impurities, or by an actual loss of metal during the process. The weight of gold as indicated by the balance will, in consequence, not represent the amount originally present in the alloy, and it is therefore necessary to control the results by assaying, side by side with the alloys under examination, " standards " or check-pieces, the composition of which is known. As, however, any error in the composition of these checks will be reflected in the result of the assay, it is preferable to use pieces of pure metal corresponding in weight to the

[1] " Ruding," vol. i., p. 209.
[2] *Notes and Queries*, Nos. 17, 19, 20, and 23. 1880.

amount which the alloys to be tested are anticipated to contain.[1] Formerly such checks of pure metal were not employed, and a small amount of silver varying from $\frac{2}{10,000}$ to $\frac{1}{1000}$ part of the initial weight of the assay piece which remained in association with the gold was consequently reckoned as gold in the assay report. It follows, therefore, that even the more recent plates, when accurately assayed, are usually found to be sensibly below the exact standards which they were intended to represent.

The experiments made with a view to ascertain the composition of the standard gold plate prepared by me, in 1873, show that the greatest variation of this plate from the exact standard does not exceed $\frac{2}{10,000}$ part; but the use of even a fairly accurate standard plate is liable to be attended with error, as the actual amount of precious metal in the amount taken for the check-piece may exceed or fall short of the true standard. It follows, therefore, that the assay reports on portions of metal tested by comparison with this check may indicate the presence of too little or too much precious metal.

The objection to the use of a standard silver plate are far greater, as the alloys used for the silver coinage, in this and in other countries, are mechanical mixtures, the molecular arrangements of which are very peculiar, and, so far as my experience goes, a plate of the legal standard cannot be prepared of uniform composition.

With regard to the use of pure gold and silver plates, it should be pointed out that, if it were possible to obtain gold and silver of absolute purity, there would be no limits to accuracy in assaying, except such as arise from operations of a purely mechanical nature. Of course, it is not possible to attain to chemical purity, and the presence of traces of impurity in the checks causes the results of assays made in comparison with them to indicate the presence of an amount of pure metal in excess of that actually present in the alloy; but as the converse can never be the case—that is to say, as the gold cannot be more than pure—no danger can arise from this cause, and the error can be easily allowed for.

[1] The corrections to be applied to a gold assay will be readily understood from the following formula:—

Let 1,000 be the weight of alloy originally taken;
p the weight of the piece of gold finally obtained;
x the actual amount of gold in the alloy expressed in thousandths;
a the weight of gold (supposed to be absolutely pure) taken as a check, which approximately equals x;
b loss or gain in weight experienced by (a) during the process of assay;
k variation of "check gold" from absolute purity, expressed in thousandths;

Then the actual amount of fine gold in the check-piece

$$= a\left(1 - \frac{k}{1000}\right),$$

and the corrected weight will be—

$$x = p - \frac{a\,k}{1000} \pm b,$$

b being added or subtracted according as it is a loss or gain.

If a be assumed to be equal to x this equation becomes—

$$= \frac{p \pm b}{1 + \frac{k}{1000}}.$$

The supplementary fine gold and silver plates, prepared in accordance with instructions I received from the Lords Commissioners of the Treasury in 1872, proved eminently satisfactory. I have not been able to prepare, or to obtain from any source, gold of greater purity, even in small quantities. The silver plate leaves little to be desired, although it is not quite as pure as silver prepared by M. Stas, in comparison with which it is as 999·95 to 1,000.

In conducting official trials of the pyx, minute accuracy is secured by a final appeal from the standard plates themselves to pure gold or pure silver.

We are now in a position to consider another question, the importance of which has long been recognised by law, and that is, the difficulty of attaining an exact standard, either of weight or fineness, in the case of all individual coins issued from a mint. The law has, for centuries, and in all nations, permitted a certain deviation from the exact standard. The amount of such "remedy," as it has always been termed in this country, has changed from time to time, but has gradually diminished as the art of coining has advanced.

It follows that, although the component parts of the alloy may not bear to each other with mathematical precision the proportion prescribed by the regulations under which they are manufactured, they may, nevertheless, be considered to be of standard fineness. The earliest reference to a "remedy" I have met with is in the reign of Saint Louis, of France, 1253,[1] who granted an allowance of ¼ carat, for the fineness of Louis d'or. The Mint agreement between King Edward I. and William de Turnemire,[2] in 1279, provides a remedy of 2½ dwts. on the pound troy of the silver coins. The law does not appear to have contemplated that the "remedy" should be systematically made use of as a source of profit, either to the Crown or to the Master of the Mint; it was rather considered to define the limits within which occasional variations of standard weight were unavoidable, and its true function has been well defined by the late M. de Jacobi, who, representing the Russian Government at the International Monetary Conference, held in Paris in 1867, said, "the remedy is not an arbitrary stipulation, but is the limit of errors which belongs to every thought, to every chemical analysis, to every composition of alloy, and as such depends on the precision of the balances, and the methods employed in the fabrication of money. It may be determined rigorously by applying the calculus of probabilities."

The Mint indentures have been drawn up in just the same spirit. Remedies were accorded "because the said moneys may not continually be made in all things according to the right standard, but, peradventure, through default of the master or workers, they shall be found sometyme too strong or too feeble in weight or alloy," but this has not prevented a very different view having been taken of the privileges accorded by them, both to the Sovereign on the one hand and the Master of the Mint on the other. Queen Mary, for instance,[3] seems to have considered that the Sovereign was entitled to add as much base metal to the coinage as the law permitted, the sum so derived, after deducting coinage expenses, to be considered seignorage, but she held that the Crown could not debase the coin, or increase the amount of base metal in it for private ends.

[1] Jean Boizard, "Traite des Monoyes," p. 25. 1692.
[2] Report on the Royal Mint, p. 41. 1849.
[3] Report on the Royal Mint, p. 39. 1849.

With regard to the action of Mint Masters in this respect, the history of the coinage abundantly proves that they frequently availed themselves of the "remedies," viewing them as a legitimate source of profit, or as a means, incidentally provided by their contracts, for reducing the current expenses of working; the best known case being probably that of Lonison, Master of the Mint in the reign of Queen Elizabeth.

The scale of remedies is fixed by the Coinage Act of 1870. At present we will only consider the remedy of fineness, which, in the case of the gold coin, has a range of $\pm\frac{2}{1000}$, and in the case of silver $\pm\frac{4}{1000}$. The gold coins of the nations who have joined the Latin Union have also a remedy of $\frac{2}{1000}$. In America the remedy in the case of the gold coins has been reduced to $\frac{1}{1000}$. "I do find," said Rice Vaughan,[1] writing in 1675, "that some men of great experience and understanding, even in this mechanical part, do hold that the moneys, both of gold and silver, may be made without any remedy to be allowed either for weight or fineness," but he subsequently adds, "I undertook this discourse of the mechanical part of money with scruple, so I do leave it with alacritie." It is certainly not the opinion of Mint officers of the present day that the remedies should be reduced to the lowest possible point, as this would involve the rejection and re-coinage of a large number of pieces before they could be permitted to leave the Mint; but, on the other hand, all agree that a persistent variation, however slight, above or below standard, has never been contemplated by law. The effect of such a mean variation would be remarkable.

If, for instance, the Mint were to issue sovereigns which were either persistently too rich or too poor in gold, to the extent actually permitted by law, a loss or profit would accrue of over £2,000 on each million coined, and a persistent variation of only $\frac{1}{10.000}$ part would be equivalent to a profit or loss of £100 a million. In Mint practice at the present day, even this comparatively small variation should be avoided, and the public trials of the pyx prove that it does not exist.

I have dwelt on these facts because the maintenance of rigid accuracy in the operations of coinage becomes of great importance in international currency. One Government might, as the late Professor Stanley Jevons pointed out, "coin money slightly inferior to the proper standard, and such money once introduced would, in virtue of Gresham's law, be difficult to dislodge." I admit, with him, that it is hardly to be supposed that a State issuing money under international obligations would wish to make a profit of one or two parts in a thousand, which the remedy would legally cover; but, nevertheless, the degree of accuracy with which the coinage is executed would be of much importance, for the following reason:—A nation would be bound by the International Convention to withdraw and re-coin such coins of other nations as might be circulating within its borders at the time they were reduced by wear below the lowest weight at which their circulation would be legal, and it follows that any deficiency of standard which might exist would have to be made good by the nation on whom the re-coinage happened to fall, and a nation coining with rigid accuracy would suffer from the shortcomings of those who did not.

[1] "Discourse of Coin and Coinage," p. 91. 1675.

ALLOYS USED FOR COINAGE.

FOURTH LECTURE.[1]

We have now to consider the means adopted to secure accuracy in the weight of coins issued from the Mint, and to examine the questions connected with the loss in weight sustained by coins during their circulation. Before the invention of coined money, the precious metals circulated by weight. Examples of such currency are presented by the gold and silver "talents" of the Schliemann collection, which bear a definite relation to the Babylonian "mina"; and so completely has the spirit of this method of circulation by weight been retained, that the best definition we possess of coins represents them as "ingots, of which the weight and fineness are certified by the integrity of the designs impressed upon the surface of the metal."[2]

Rice Vaughan,[3] whom I have before quoted, has some interesting remarks on this point in the section of his little work devoted to the consideration "of coining moneys without distinction of weights." He says the proposition is, "that there should be coined no pieces of a certain (*i.e.*, definite) weight, either of gold or silver, but that, the alloy being certain, the weight should remain uncertain; all money now current should be valued by a certain weight." For example, every ounce of silver should be valued at five shillings and every ounce of gold at such a proportion as shall be thought most equal. He points out that, among other incidental advantages, this plan would prevent the "culling, washing, and clipping," of money—that is, its fraudulent reduction in weight; but, on the other hand, the objection would be, as he says, "the extreme molestation which the people should receive in the practice of it, when every man should be bound to carry scales in his pocket, and upon every little payment be bound to weigh their money." Few people at the present day bear in mind that this is precisely what, in the case of the gold coin, the existing law requires them to do, for the Coinage Act of 1870, now in force, directs, in Section 7, that "where any gold coin of the realm is below the current weight provided by this Act, every person shall, by himself or others, cut, break, or deface such coin tendered to him in payment, and the person tendering the same shall bear the loss." Compliance with this demand would, of course, render it necessary for each individual, who has reason to expect the tender of a sovereign, to carry scales and weights, as well as shears to cut such pieces as should be found to be deficient in weight.

It will be well for us to examine—1st, what degree of accuracy as to weight the law requires in pieces issued by the Mint; and 2nd, how long gold coins may be expected to circulate without incurring the "extreme penalty of the law," which takes the same view of coins as is expressed in Butler's "Erewhon" with regard to humanity, and considers defective organisation and decrepitude in a coin to be criminal, and punishable by "cutting and defacing." Mr. John Biddulph Martin, whom I shall again have occasion to quote, well observes, "We are wont to speak of the life of a coin, but whereas the term 'life' is in all other cases associated with a

[1] *Journ. Soc. of Arts*, 1884, vol. xxxii., p. 911
[2] Stanley Jevons, "Money," p. 57. 1876.
[3] "A Discourse of Coin and Coinage," p. 214. 1675.

period of growth, of maturity, and of decay, in this instance the process is one of degradation only."

The first schedule of the Coinage Act of 1870 prescribes the weight at which each coin shall be issued; it also defines the lowest weight at which the gold coins may be permitted to circulate, and it sets forth the "remedy" of weight—that is, the range above or below the exact standard within which the issue of coins would be legal. The silver and bronze coins, being merely tokens, have no "least current weight," but are withdrawn from circulation, and re-coined when they become defaced by wear. The standard weight of a sovereign is 123·27447 grains, the remedy is $\pm$ 0·2 of a grain, and the least current weight 122·5 grains. In the case of the half-sovereign, the standard weight is 61·63723 grains, the "remedy" $\pm$ 0·1, and the least current weight 61·125 grains. In order to ensure that the coins issued from the Mint shall be well within the remedy allowed by law, it is necessary to adopt in practice a still more minute margin, or allowance for unavoidable error. The "working remedy" adopted in the Mint in the case of the sovereign is, therefore, fixed at 0·17 of a grain, instead of the 0·20 which the law allows, and the weight which denotes whether a sovereign is or is not within the remedy is represented by a piece of wire of fine gold, 0·1355 inch in length, and 0·018 inch in diameter, and weighing 0·17 of a grain. It will be obvious that the possibility of restricting the weight of coin within such narrow limits entirely depends on the degree of accuracy which may be attained by the process of rolling the strips of metal from which the discs destined to form the finished coin are cut; and we have already seen, in the first lecture, that in the case of the fillet prepared for the manufacture of the half-sovereign, a variation of $\frac{1}{20,000}$ of an inch above or below the accurate thickness, or a range of $\frac{1}{10,000}$ of an inch in the thickness of the fillet, would cause the rejection of the coin, on the ground of excess or deficiency of weight. The question then arises, Is it not possible to supplement the operation of rolling by some mechanical operation, conducted on the blanks themselves, in order to bring them within a closer approximation to the exact weight? The problem has long proved an attractive one in Mints, but the earliest suggestion I can find for securing absolute accuracy in weight occurs in the "Records of the Scotch Mint,"[1] from which it appears that J. Acheson claimed, in 1597, to have discovered a method of making coins so that none shall be "ane grane heavier or lichter nor another."

On the Continent it is very generally the practice to adjust blanks by the aid of a file, the weighing being performed by hand; the process is, however, open to the objection that the marks of the file are never quite obliterated when the blanks are struck into coin, and the same objection applies to most of the machines that remove a fine shaving of metal from the surface of the blank. An additional objection to such a mechanical adjustment of blanks arises from the tendency, in Mints where it is adopted, to produce "too heavy" blanks in the rolling and cutting departments, as it is impossible to adjust blanks which are too light. Some years ago, Mr. J. M. Napier[2] devised for the Indian Mints an automatic machine of great beauty, which first ascertains how much it is necessary to cut from each blank in order to reduce it to the standard weight, and then removes the necessary amount

[1] "Records of the Coinage of Scotland," by R. W. Cochran-Patrick, Esq., M.P. 1876. Introduction, p. cix.

[2] Patent, No. 108. 1866.

of metal and no more. The initial cost of such machinery is, however, considerable. Another machine, having the same object in view, has been devised by M. Seyss.[1]

Chemical aid has not been wanting in the attempt to solve the question of the adjustment of blanks. In 1849, M. Diereck, Director of the Mint in Paris, endeavoured to substitute a chemical for a mechanical treatment by submitting the heavy gold blanks to *aqua regia*, which, it was anticipated, would bring them within the prescribed limits of accuracy, by dissolving away metal. The results were not satisfactory, and the attempt was abandoned.

Having myself attacked the question in 1870, I may, perhaps, be permitted to refer to the results which attended my experiments. It was found that gold, alloyed with copper, might be removed from heavy blanks with singular regularity by means of a suitable solvent aided by a battery. The blanks were arranged in a frame of wood, and submitted to the action of a solution of cyanide of potassium, the heavy blanks forming the dissolving pole of the battery. The process was not used in the London Mint, as it became evident that it could not replace the present system, under which finished coins alone are weighed, and the manufacture of good coin only is paid for. The late M. de Jacobi, one of the earliest workers in the field of electro-metallurgy, visited my laboratory while the first experiments were in progress, and we discussed the possibility of re-depositing the metal removed from the heavy blanks on those that were too light, the problem being to obtain a tenacious film.

I was greatly interested to find, long after my experiments were made, that an eminent firm of electrotypers had suggested officially that the worn gold coins in circulation could be restored to the legal weight by the electric deposition of a film of gold on the surfaces. The process was introduced into the Bombay Mint, in 1873, by the late Mr. L. G. Hines, who transferred the metal dissolved from the heavy blanks to blanks which are too light, the latter being by this means raised to the prescribed weight. Its importance in mints where its use is possible may be gathered from the fact that, in the Indian mints, no less than 1,300 tons of silver were converted into coin in one year (1879), so that the saving effected by its use must be considerable.

Whether or not a method for adjusting the blanks be adopted, the finished coin must be weighed before it leaves the Mint, and this, as before stated, is the great obstacle to the introduction of the electro-chemical method into the English Mint. In former times the weighing was effected only in bulk, but more recently individual pieces have been weighed in this country. I have already pointed out that the weighing may be effected by hand, and this method is very generally adopted on the Continent and in America, where each operator is provided with a delicate pair of scales.

In the Mint of this country, very beautiful automatic machines are used, for a full description of which reference may be made to the "Encyclopædia Britannica."[2] (*Note.*—The general nature of the appliance was made clear by the aid of a model.) The balance was originally devised in 1851 by the late Mr. William Cotton, of the Bank of England, and has since been improved by the officers of the Mint, and by Mr. J. M. Napier, who has secured several patents in connection with this machine.

[1] *Dingler's Polytechnisches Journal*, ccxlv., 61; plate 6. 1882.
[2] Ninth edition, art. "Mint."

In the Vienna Mint, a balance devised by Herr Seyss is employed, which depends upon a somewhat different principle. The beam resembles that of an ordinary balance, with pans suspended from it; one pan contains the weight, and a slide brings forward the coin to the other pan; the depression of the beam produced by a heavy coin brings the balance pan opposite one of several slits, the lowest slit corresponding with the extreme depression of the beam produced by a very heavy coin. The pan is then momentarily fixed, and the coin is allowed to pass away into the slit against which it stands. If coin is very light, the pan which contains it will rise and stand opposite the highest of the series of slits.

The life of a coin, after it leaves the Mint, may now be traced, and it will be seen that the conditions of its existence are far less severe in modern than they were in ancient times. The actual wear to which coins are subjected may, no doubt, be rougher at the present day than in the past; but, on the other hand, they are not subject to anything like the same extent to ill-treatment from enemies in the shape of clippers and sweaters.

It is difficult to over-rate the importance of some system of protecting the edge of the coin against fraudulent treatment, and it is hardly less difficult to understand, at the present day, the extent to which the ill-shaped hammered coins were tampered with. The earliest protection seems to have been afforded by a circle or beaded ring on the surfaces of the coin, and that such circles have been used from early times is proved by the fact that many Greek coins bear them. Attention is specially directed to the outer circle in an enactment of King Henry VII., which provides that "every piece is to have a circle about the upper part thereof, and also that all manner of gold hereafter to be coined shall have the whole sculpture without lacking any part thereof, to the intent that the King's subjects might have perfect knowledge, by that circle or sculpture, when the coins were clipped or not." No protection, however, is as efficient as the addition of letterings or devices round the edge of the coins. I have already stated in the first lecture that the practice of marking the edges was adopted, for another reason, in Roman times in the case of the *Nummi Serrati*, mentioned by Tacitus.

Coins may be fraudulently reduced in weight by the action of a solvent aided by a battery, but there is reason to believe that the practice is only carried on to a very limited extent.

Removal of metal by drilling holes and filling them up by base metal has sometimes been resorted to, and the Mint Museum contains interesting examples of American coins which have been sawn so as to leave two thin flat discs, which have subsequently been soldered over a disc of base metal, the precious inside of the coin having been removed. It has been proposed to make the American gold double-eagle dish-shaped, in order to render the centre so thin as to prevent this method of falsification. In mediæval times, tampering with the coin caused the gravest anxiety, and was punished with dreadful severity.

In 1381, the first equivalent of the modern Royal Commission on the Coinage met, and the following was the evidence, or rather were the recommendations, of the individuals who took part in it. Richard Leyc advised that the practice of clipping the gold coin could only be checked by a proclamation directing individuals to weigh coins when they took them, and

Richard Aylesbury, a goldsmith, also held that gold pieces which had been reduced by clipping should be universally weighed by those who received them.[1] I will take only a few more historical instances of instructions as to weighing the coins tendered to individuals. The Mint Records [2] contain a copy of a proclamation given in the 17th year of King James I., which states that "the people, instead of refusing such light gold moneys as were without the remedies . . . . do now for the most part accept in payments, indifferently and promiscuously, all such coins whatsoever tendered unto them, without weighing," which shows that the practice of weighing the coin had been adopted, and was falling into disuse. In 1619, the person who tendered the gold coin was instructed to give twopence for every grain the coin was light, and individuals were directed to brand every piece abnormally light by striking a hole through it, returning such pieces to the owners thereof, thus re-affirming a proclamation made in 1587 by Queen Elizabeth, which directed that the defective coins should be "stricken through and cut into pieces." In 1632, it is stated that "in and about London and Westminster people carried scales in their pockets, to weigh gold on all occasions." [3] I mention these facts to show that the directions of the present law (Coinage Act, 1870), as to the cutting and defacing of worn coin rest on ancient precept.

The condition of the silver currency in the end of the seventeenth century may be gathered from the statement of Lowndes, who computed the amount of all the silver moneys coined in the reigns of Queen Elizabeth, James I., and Charles I., at £15,109,476. Writing in 1695, and allowing for the sums coined in the reigns of Charles II., James II., and William and Mary, he did not consider that the silver circulation consisted of more than £5,600,000, of which only £1,600,000 was heavy; [4] and he further pointed out, as the result of careful weighing of the coin in bulk, that the weight of the "moneys commonly current are diminished near one-half." Not, it must be remembered, merely by legitimate wear, but by the fraudulent practice of "clipping," from which, I believe, modern coinages suffer to a hardly appreciable extent.

It is now necessary to consider the conditions affecting the circulation of a metallic currency, more especially as regards its power of resisting legitimate wear. An experimental enquiry conducted by the officers of the Mint towards the close of the last century showed that $78\frac{1}{10}$ of the shillings then in circulation were required to make a pound weight, which should have been represented by 62 shillings; eleven years later, $82\frac{9}{10}$ shillings weighed a pound. With regard to the gold coinage, the Mint officers found, in 1807, that 1,000 guineas withdrawn from circulation had lost 19s. per cent. in value. Parcels of 300 sovereigns, coined in each of the years 1817-21-25-29, were weighed by the officers of the Mint in 1853, and the results proved that they had sustained an average rate of wear of 0·047 grain per annum.

The rate of wear, in the case of gold coins, is dealt with by Jacob [5]; but we owe an authoritative determination of the annual rate of wear of the gold coin to the late Professor W. Stanley Jevons, F.R.S.[6]—formerly assayer of

[1] "Ruding," vol. i., p. 240.
[2] "Record Book," vol. i., p. 56.
[3] "Ruding," vol. i., p. 386.
[4] "Essay for Amendment of the Silver Coins," p. 105. 1695.
[5] "The Precious Metals," vol. ii., p. 168. 1831.
[6] *Journal of the Statistical Society*. 1868.

the Sydney branch of the Royal Mint, and subsequently Professor of Political Economy at University College, London—who brought to the consideration of the question an acute intellect and perfect knowledge of the conditions which govern the metallic currency. He proved, as the result of an exhaustive enquiry, that "just about eighteen years' wear will reduce a sovereign below its point of legal currency"; and he shows conclusively that the average rate of wear per annum of the sovereign is 0·043 grain, which led to the conclusion that, at the time he wrote (1868), "31·5 per cent. of the whole of the sovereigns in the kingdom are now no longer of legal currency." He estimated the annual average wear of the half-sovereign at 0·069 grain. Mr. Martin[1] has since repeated and extended Professor Jevons's inquiry. He has greatly added to the value of the work by bringing it down to the present time; and his researches, which deal with no less than 105,364 sovereigns, confirm, in a remarkable manner, the average rate of wear deduced by Professor Jevons, who adopted a different method of calculation. It may safely be assumed, therefore, that any sovereign which has been in circulation more than eighteen years has been reduced to a point at which it is not legally current, and should, therefore, be withdrawn from circulation, in order that it may be re-coined.

The questions now present themselves, Can this average rate of wear be diminished? Is the form of the coin well adapted to enable it to resist wear; and is it possible to adopt a more durable alloy for our gold coinage? First, with regard to the form; no doubt a sphere which contains the maximum weight in the smallest surface is better adapted than a disc to resist the abrading influence of friction, and it follows, therefore, that the Siamese money, which is nearly globular, will retain its weight longer than any other coin now in circulation.

A short cylinder is the geometrical form which, next to the sphere, presents the smallest surface for the greatest weight, and, consequently, in order to reduce the wear of coins to a minimum, their thickness should be equal to their diameter. Such a form would present many inconveniences; but, on the other hand, coins should not be made too thin, and much may be gained by even a small approach to theoretical requirements. A good practical rule for calculating the most useful diameter of a coin from its weight is given by the following formula:—

$$D = P\sqrt[3]{G}.$$

D = Diameter in millimetres.
G = Weight in grammes.
P = A certain number found by experiment.

Take the cube root of the weight of the coin, multiply by the number for the particular coin, and this gives the most suitable diameter in millimetres. The value of P for all kinds of gold coins is 11·3.[2]

I have thought it advisable to make the above reference to the matter, although it is not likely that the form of our coins will ever be greatly

[1] *Journal of the Institute of Bankers*, June, 1882.

[2] Karmarsch, "Handbuch der Mechanischen Technologie," vol. i., p. 551. Hanover, 1876.

modified. The mean thickness of the coin does not differ much from the initial thickness of the blank, because in virtue of the "flow" of metals, to which allusion has already been made, the portions of metal diminished in thickness are about balanced by the raised part of the device. Sharp new coins do not wear much more rapidly than old ones, as is shown by the experiments of Professor Jevons and Mr. Martin—that is, the rate of wear of coins at different periods of their career is fairly normal. There is no doubt that a coin in high relief becomes disfigured much sooner than one in low relief, as the unity of a design is greatly impaired by the loss of a prominent feature, and the lovely Renaissance works in low relief (now before you) present a much better appearance after prolonged circulation than their classical predecessors, which are almost lenticular in form. The power of the metal to resist, not wear, but deformation by impact, therefore, demands attention, and from this point of view a soft metal is far less useful than a hard one. Coins of lead, for instance, have been found, in experiments to which reference will be made presently, to become rapidly defaced, and reduced to the state of mere blanks, when submitted to mutual action in a revolving drum. Coins of pure gold also become rapidly defaced, although their weight is but little reduced by such treatment. As has already been pointed out, the reason for using an alloy instead of pure metal is the greater durability of the former, and accurate experiments on this point have not been wanting. Their history may be briefly stated as follows :—In 1792, the unfortunate French Statesman Clavière [1] proposed that pure metals should be used for coinage, and that they should be current by weight. The Académie des Sciences was consulted on the subject, and experiments made by this distinguished body [2] showed that while pure metals were rapidly reduced in weight by friction, the addition of even a small amount of base metal had a notable effect in enabling the metals to resist abrasion by wear. In 1798, the Privy Council appointed a committee "to take into consideration the state of the coins of this realm," and they directed Mr. Henry Cavendish, F.R.S., and Mr. Charles Hatchett, to ascertain experimentally whether the loss of gold coins by wear was "occasioned by any defect, either in the quality of the standard gold, or the figure or impression of the coins." The result was an elaborate investigation, conducted by Mr. Hatchett,[3] on the "comparative wear of gold," the results of which have since been frequently quoted, and have, in fact, become classical. Hatchett operated both on unstamped blanks, and on discs struck by dies, which produced small "rounded prominences, regularly disposed over the surface of the coin." Such blanks, or coined discs, were arranged in two frames, so that the flat surfaces of the metal could rub against each other when the frames were pressed together. Each frame was moved rapidly backwards and forwards by suitable mechanism, the path of each frame being at right angles to the other. The discs were in this way subjected to mutual friction, and the gearing was so devised that while one frame was moving with its greatest velocity, the other was at the extremity of its path, the result being that the coins were prevented from moving always in the same line. The numbers of "revolutions" or contacts of the pieces varied from 20,680 to 229,000. He also used a cubical box of 8 inches, in

[1] "Traite des Monnaies," par. P. F. Bonneville, p. xxiii. 1806.
[2] *Annales de Chimie* (1793), tome xvi., p. 230.
[3] *Phil. Trans. Roy. Soc.*, 1803, p. 43.

the side, in which the coins were made to revolve; and the discs were also rubbed on a table covered with either flour, fine chalk, or metallic filings, fixed in isinglass. Hatchett's main conclusion was that the "extraordinary loss which the gold coin of the kingdom is stated to have sustained within a certain limited time cannot, with even a shadow of probability, be attributed to any important defect in the composition or quality of the standard gold."[1] He further observes "that the experiments on the various alloys of standard gold (that is, gold standardised with various metals) concur with established practice and opinion to prove that only two of the metals—viz., silver and copper—are proper to be employed in the reduction of fine gold to standard for the purpose of coin." Notwithstanding the care and skill employed by Hatchett in conducting his experiments, some of his deductions appear to demand confirmation. The subject possesses additional interest at the present time, because it is probable that much of the light gold coin now in circulation will soon be withdrawn; and it has, therefore, been considered advisable that Mr. R. A. Hill, Superintendent of the Operative Department, and myself should resume an investigation on the relative wear of coins of different metals and alloys, which was begun by one of us during the Mastership of the late Mr. Graham. After several preliminary experiments, in which a sliding motion was given to pieces of metal along a smooth surface of oak, we satisfied ourselves that revolving the pieces in a box represents more faithfully the kind of friction to which coins are subjected in the varying conditions of their circulation, and this view was fortified by the opinion of the late Professor Jevons. We addressed ourselves mainly to ascertaining whether the alloy used for the British gold coin, the standard of which is 916·6, is, or is not, more durable than the alloy of 900 fine, which is so widely used by other nations; and we are satisfied that the experimental evidence proves, as regards rate of wear, that there is not much to choose between standards 916·6 and 900. On the other hand, differences in mechanical treatment, resulting from a heavy as compared with a light blow, or in thermal changes produced by annealing, exert greater influence on the rate of wear than the small variation in composition comprised between the limits 900 and 916·6. We agree with the view taken by M. Feer-Herzog[2] that differences of wear of coins of these two alloys is very slight.

Our experiments are in progress, but the results hitherto obtained are published in the Mint Report for last year.[3]

The use of aluminium has often been suggested for the manufacture of subsidiary coins, this metal being known to possess great tenacity when equal volumes of it and other metals are compared. We have been much interested to observe that coins of aluminium, especially if they be alloyed with about 2 per cent. of nickel, are very durable, as are also coins of pure nickel; but in one case the durability results from toughness, and in the other from hardness.

There is one other point in connection with the gold currency to which I would now direct your attention. The Coinage Act of 1870 fixes the remedy on each individual piece, and not, as was the case formerly, on the pound weight of the coin. The object of this provision is to prevent the "culling"

[1] *Loc. cit.*, p. 190.
[2] See "Enquête sur la question Monétaire" (Paris, 1792), vol. i., p. 344.
[3] "Fourteenth Report of the Mint," p. 45, 1883.

of heavy pieces, which would be a profitable transaction if the inequalities of weight were considerable. The heavy pieces so selected might either be exported or used in the arts, and the annals of the coinage abundantly indicate the extent to which the practice was carried on in former times. A notable case occurred in 1637,[1] when the Attorney-General charged several persons before the Star Chamber with "culling out the weightiest coins, and with melting down his Majesty's moneys into bullion"; and, on examination, it appeared "that between the years 1626-1631 one Timothy Eman culled £500,000 a year, which yielded £7,000 or £8,000 of heavy moneys yearly, and in five years he melted down £15,000, his profit amounting to £100." Another offender was Violet, whose name deserves mention, as his work, "An Appeal to Cæsar," contains so much curious information as to the export of bullion.[2]

The amount of gold actually in circulation (1884)[3] is estimated to be £100,000,000, but the coinage returns show that the amount of sovereigns and half-sovereigns issued since 1816, when their coinage was begun, is £247,521,429. What, then, has become of the 147 millions not in circulation? The coinage returns show that between the years 1864-83 £57,492,842 in sovereigns were coined. A considerable proportion of these have been exported never to return. The following figures, which I offer with some hesitation, as they may not be rigidly accurate, show that, while during the same period sovereigns were exported and imported, the excess of exports over imports was no less than £25,991,445, or a yearly average of £1,299,572.

With regard to the disappearance of gold coins from circulation, Prof. Jevons has some observations of extraordinary interest. He says it appears "that of the sovereigns coined in 1817-19, not more than one-fiftieth part remain in circulation; and the proportion rises until, between the years 1840-58, it is about one-third." He suggests in his paper that these curves should be plotted graphically. In both cases there is an elevation in the period 1840-45, arising probably from the re-coinage of the years 1841-43, when £14,000,000 of gold coin were called in and re-distributed in an unusual manner, so that more than a common proportion became fixed in the circulation. The most important peculiarity of the numbers is the very small increase which takes place in the proportion of sovereigns preserved between the years 1832 and 1854: this indicates that there is a residuum of coin which is no longer subject to be exported or withdrawn, like the rest of the circulation; for if the proportions of coins exported were taken indifferently, the curve would rise as rapidly as is the case with the half-sovereign curve, those coins not being liable to exportation.

It will be evident, therefore, that in tracing the analogy between the life of a coin and ordinary vital phenomena, we are abruptly checked by observing that the "fittest" coins are not those which survive as the fittest—that is, the heavy ones drop out of the struggle of active circulation they were created to sustain, and are either exported or exist as part of a "hoard" of coin. It may, of course, be urged on this ground that a full-weight coin, issued to the public without charge, is not the fittest to retain its place in

[1] "Ruding," vol. i., p. 389.

[2] "An Appeal to Cæsar," by Thomas Violet, of London. 1660.

[3] The amount of gold coin estimated to be in circulation in the United Kingdom at the end of 1910 was £113,000,000 (41st Mint Report, 1910).

circulation, and that a small amount of metal lost by wear really tends to its preservation.

With that Darwinian problem I must bring these lectures to a close.[1] You have seen the great change and depreciations through which the "alloys used for coinage" have passed in times gone by, but there is no probability that in this country similar changes will take place in the future, and I cannot find better words to offer you than a quotation from Professor Jevons, whose perfect grasp of the question of metallic currency enabled him to realise its difficulties in a way few of us are able to do. He points out that, in times past, the rulers of nations have been the most notorious false coiners and depreciators of the currency; but that now "the danger lies quite in the opposite direction—that popular governments will not venture upon the most obvious and necessary improvement of the monetary system without obtaining a concurrence of popular opinion in its favour; while the people, influenced by habit, and with little knowledge of the subject, will never be able to agree upon the best scheme."

I can say with Rice Vaughan that "my scope was not to render the reader able to find out the fittest course to govern this matter of money and coin, but able to judge of what should be propounded by others"; but we need no longer fear the state of things described by him when he says "that for want of that ability the wisest States and the greatest Councils of Christendom, for many ages, have been abused by mysterious names and perplexed subtleties of Mint-men."

[1] Since the above was written I find that Mr. J. B. Martin incidentally pointed to this analogy in a paper read before the Institute of Bankers in March last.

"THE QUEEN'S ASSAY MASTER."[1]

"Who knows . . . whether there be not more remarkable persons forgot, than any that stand remembered in the known account of time."—Sir THOMAS BROWNE.

The titles of various officers of State, such as the "Queen's Remembrancer" and the Queen's "Master of the Horse" are familiar enough, but that of King's or Queen's "Assay Master" is less known, although borne by a long list of officers, who, from the time of King Henry III., have discharged most important duties. In the case of Assay Masters "oblivion blindly scattereth her poppy"; still their influence has not been without record in history, for they have answered for the purity of vast sums of money, and have thus indirectly represented the financial integrity of the nation. We are now so accustomed to accept implicitly the belief in the excellence of large masses of coin, and the time when the nation suffered from the use, in coinage, of metal which was often far from being as good as it professed to be, seems so remote, as to make it difficult to realise the national distress which found expression in a proclamation by Queen Elizabeth, when she declared that "by the long-suffering of the base monies . . . the ancient and singular honour and estimation which the Realm of England had . . . is decayed and vanished away." Still less do we think of the precautions which are adopted for ensuring that the provisions of the law as to the composition of coin are strictly observed, and, if people reflect upon the matter at all, their mental attitude is rather that of a certain knight, whose views, set forth by an early political economist, William Stafford, in 1581, did not "enable him to perceave what hinderance it should be to the Realm to have this metal more than that for coyne, seeing that the coyne is but a token to goe from man to man when it is stricken with the Prince's seale." The material to be used for coin is not, however, a matter of indifference. It must be of such a nature as to ensure its being readily acceptable, and further, as Nicholas Oresme, tutor to Charles V. of France, pointed out in the fourteenth century, it must be of value, *materia pretiosa et cara;* or, as a later writer, Rice Vaughan, said in 1675, "money should be made of material which is not too common, something not easy to be consumed by use, or spoiled for want of use." Now coins of pure gold or silver would soon, owing to their softness, be spoilt by wear, and, therefore, a certain amount of base metal, seldom more than one-tenth part, is added to harden the metal, and the resulting mixture is called an *alloy*. The correctness of the weight of a coin can at all times be verified by its possessor without difficulty, but the device on its face—the "Prince's seale"—is the only pledge he can have of its correctness in composition, and in a very early stage of civilisation such an impression became necessary, because it "was speedily found out and discovered that weight alone was not a sufficient measure for gold and silver, by reason that they are subject to mixture, and, therefore, there was an examination made of the pureness of them, and a mark impressed upon them to show that they were approved." The officer in the Mint who is responsible for the due admixture of the precious with the base metal, or,

[1] An article by Roberts-Austen which appeared in *Murray's Magazine* in 1887. It is reproduced here by the kind permission of Mr. John Murray.

in other words, for the composition of the alloy, has for centuries been called the King's or Queen's Assay Master.[1] He submits the alloy used for coinage to a test of great delicacy, but which can be performed with more rapidity than a minute and exhaustive chemical analysis, such a test being termed an "assay." The word is, however, simply the old one meaning trial, and, except as applied to the testing of metals, "assay" is now an archaic form of "essay." This is well illustrated by a comparison of the couplets occurring in Spencer's "Faery Queene," where, in the description of Mammon's laboratory he says :—

> "And every fiend his busy pains applied
> To melt the golden metal ready to be tried."

The word applied to the testing of gold is *tried*, while in the previous verse Mammon sets gold before Sir Guyon :—

> "For well he weened that so glorious bait,
> Would tempt his guest to take thereof assay,"

meaning, of course, that he would partake of the gold displayed in such profusion. It may further be pointed out that the word "alloy" is often employed in two senses, being applied to the base metal which is added to the precious one, as well as to the mass of the mixed metals. This confusion probably arose from an erroneous fancy that the old French *alei* was equivalent to *à loi*, so that the word, meaning originally "combination," "union," came to be used specially of the mixing of baser metals with gold or silver in coin, so as to bring it to the recognised standard. An early Italian writer on metals, Biringuccio, used the word alloy with perfect accuracy in 1540, when he said, "I have told you," speaking of the gold alloys, "that an alloy only signifies an intimate association (*damicabile amicitia*) of one metal and another." Poets have, however, fostered the misuse of the word by employing such phrases as "pleasure without alloy"; or, to take another instance, in the sentence in which John Fletcher, employing an analogy borrowed from the language of the Mint, says that :—

> "Affliction when I know it, is but this,
> A deep alloy whereby man tougher is
> To bear the hammer."

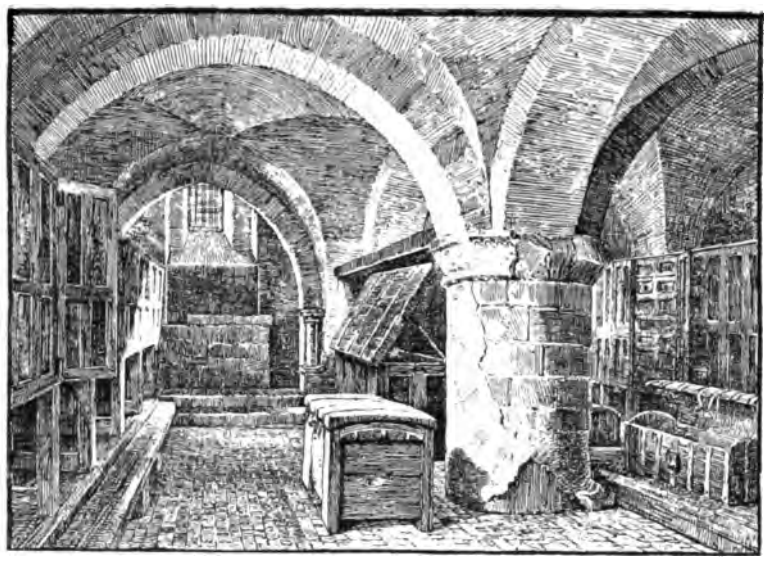
In the "Religio Medici," Sir Thomas Browne writes with his usual accuracy when he describes one who asks alms of him "as having a soul of the *same alloy* as our own"—that is, of the same constitution.

The strange fascination which the attempt to actually produce gold possessed for the earliest scientific workers has often been pointed out, but it is wonderful how persistently literature retains a hold on words connected with the manipulation of the precious metal. To take only a few instances, gold, which is tried by fire, suggests to the Hebrew writers the trial to which the soul is subjected, while Shakespeare also uses a simile borrowed from the Mint in the sentence, "Now do I play the touch, to try if you be current gold indeed"; and Thackeray concludes one of his papers by saying, "Ah, friend, may our coin, battered, clipped, and defaced though it be, be proved to be sterling silver in the day of the great Assay."

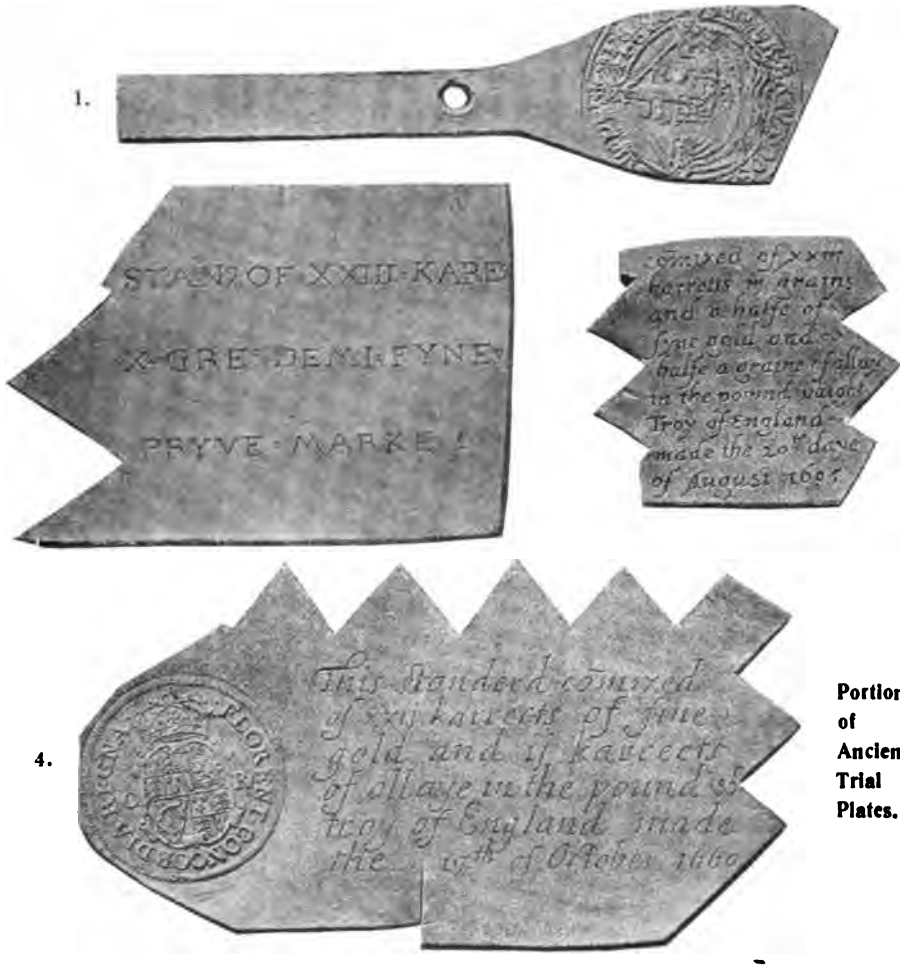
[1] The use of this title was discontinued in 1851 except for executive purposes under certain Statutes.

Plate IV.]

[*To face page* 69.



THE CHAPEL OF THE PYX (from an Original Drawing by A. H. Hallam Murray).



Portions of Ancient Trial Plates.

The history of the changes in the alloys used for the gold and silver coinage is too long to be told here. It will be sufficient to say that the gold coinage begins in the reign of King Henry III., the finest gold being used. Edward III. projected a gold coinage which contained a very small amount of base metal; Henry VIII. introduced the standard now in use, which contains a little over 8 per cent. of base metal, the standard fineness being expressed as 916·66 parts of gold in 1,000, or 22 carat fine, and ultimately he caused coins to be issued of the standard 833·33—that is, with over 16 per cent. of base metal. Edward VI. improved the fineness of the gold currency, and Queen Elizabeth completed his work; since her time the standard of the gold coinage has remained unaltered. The vicissitudes through which the silver coinage has passed are more numerous than those which have affected the gold. Its standard fell to the lowest point in the fourth year of Edward VI., when the coin only contained one-fourth of its weight of silver, the rest being base metal. The restoration of the standard of the silver was mainly effected in the reign of Queen Elizabeth, and these coins have not been since debased.

[Here followed an account of the methods by which the fineness of bullion is determined. It is substantially the same as that given in the Third Cantor Lecture (pp. 47-56)].

Some means of checking the results must be provided, and these "trial plates," by which silver and gold have been tested, possess, it seems to me, an amount of interest that can hardly be over-rated. The oldest of them, a silver plate, is alluded to as follows in the *Rotulus de Moneta*, of the 7th and 8th years of King Edward I.:—"*Premerement qe hom doit fere un estandart, qe doit demorer al Escheker, ou en quel lieu qe nostre seignor le Roy vodra,*" and in 1326 there is a record of the provision of two silver plates for testing the silver coined by King Edward II., for his Duchy of Aquitaine, "one plate to be of the just weight before the fire, and the other such as it (the metal tested) ought to be after the assays."

The trial plates were formerly kept in the Pyx Chapel in Westminster Abbey, of which an illustration is given in the accompanying plate. The chapel is thus described by the late Dean Stanley, writing in 1867. "In the eastern cloister is a solid door, which can never be opened except in the joint presence of the Treasurer and Chancellor of the Exchequer, and the Comptroller of the Exchequer, or their representatives, bearing the six huge keys that alone can admit to the chamber within. That chamber, which belongs to the Norman substructure beneath the original monastic dormitory, is no less than the Treasury of England. . . . Hither were brought the most cherished possessions of the State: the Regalia of the Saxon Monarchy; the Black Rood of St. Margaret's. . . . The Pyx chest alone remains, but the Pyx Chapel continues, like the enchanted cave of Toledo or Covadonga, the original hiding-place of England's gold—the one undoubted relic of the Confessor's architecture—the one solid block of the fabric of the monarchy . . . a testimony at once to the sacredness of the Abbey, and to the independence of the Crown." The Chapel contains an altar-tomb believed to be that of Hugolin, the first Chancellor of the Exchequer, on which there is a circular disc-shaped cavity where a small furnace may have rested, if,

as is probable, the Trial of the Pyx was at one time conducted in this building. The trial plates were removed in 1842 from the Pyx Chapel to the office of the Queen's Assay Master in the Mint. Each plate is divided into several portions, and, as with the old Exchequer "tallies," this division was effected in rough serrations, so that portions of the original plate entrusted to the different officers could be readily identified. All the principal changes which have taken place in the standard fineness of the British coinage are represented in the thirty plates, the residual portions of which are preserved in the Mint. Facsimile illustrations are given of some of the more interesting. No. 1 was made in the 17th year of King Edward IV. (1477); its standard fineness is 994·8 parts of gold pure in 1,000, which represents that originally adopted by King Edward III. in the year 1345. No. 2 is the first plate bearing an inscription, and the "pryve marke" (a pomegranate) is the same as that borne by the sovereigns and "angels" issued by Queen Mary in 1553. The standard fineness now in use for the gold coinage, 916·66, was first introduced by King Henry VIII., and James I. issued coins of this standard; but in 1605 he restored the standard to 994·8, when the plate represented by No. 3 was made. King Charles II., soon after his accession, ordered two gold plates to be prepared, rejecting those which had been made under the Commonwealth; No. 4 represents one of these plates, and is of the standard 916·66 now in use; no coins of the old standard 994·8 have been issued since the year 1640. All the plates, however, possess peculiar interest, for they symbolize centuries of responsibilities, which I am fully sensible it is a privilege to be permitted to continue.

The offices of Fusor and Miles Argentarius were, Madox says, in his history of the Exchequer, "Sergeanties" of the Exchequer; they would appear to be older than the office of King's Assay Master, which is, however, one of considerable antiquity. The list of names given by Ruding, the historian of the coinage, begins with those of Robert de Grettone and Galfridus de Frowie, Assay Masters in the sixth year of King Henry III. (1221). The latter was probably a member of the family of Frowyke, well known in the history of the City of London. These men were followed by Richard Bonaventure; and he by Bartholomew de Castello; but the limits of this article will only render it possible to notice the names of the more prominent of those who held the office. In 1274 a very remarkable man, Gregory de Rokesley, was appointed Assay Master by King Edward I. He was subsequently Ambassador to Flanders and Lord Mayor of London, and is described as being an individual of resolute and determined character, who, during his Mayoralty, refused to give the King's Treasurer an account of how the peace of the City of London was kept, and, the King being displeased, the office of Mayor was suspended; Rokesley was, however, again elected Mayor in 1285. Passing over succeeding Assay Masters, the reign of Henry VIII. brings us to Lawrence Warren, who was, so far as can be ascertained, the only one against whom there is any unfavourable record, for it appears that he received a pardon under the Great Seal of King Edward VI. "for all offences against the coin."

The nature of the office and its emoluments in the sixteenth century is well shown by a contemporary description of the duties of William Humphreys, Assay Master to Queen Elizabeth, who "stood charged to the Queen's Highness . . . for the true makynge of the moneys." He was to have "yerely

for his fee £66 13s. 4d.," and his name is interesting because in 1565 he was granted in conjunction with Christopher Schutz—" a man of great cunning, knowledge, and experience "—the first patent for making brass in England, an alloy which has since attained so much importance throughout the world. Humphreys and his partner, Schutz, also received a grant from the Queen of " all mines, minerals, and subterranean treasures, which should be found in all other parts of England (not mentioned in the former patent), or within the English pale of Ireland, by the name of gold, silver, copper, tin, etc." Humphreys thus became a very important person in connection with the corporation called the " Society of the Minerals and Battery Works," and also with the " Society for the Mines Royal," of which latter William, Earl of Pembroke, was first governor, and Robert, Earl of Leicester, Lord Monjoy, and Sir William Cecill, assistants.

It is worthy of notice that in this reign Mr. John Bull was especially appointed for the invidious duty of " assaying the base coinage for Ireland."

From the time of Queen Elizabeth the Assay Masters had rather to devote their energies to ensuring minute accuracy in the standard fineness of the coinage than to preventing its debasement. The grave objections to debasing the coins were well understood, and there were many outside the Mint to protest strenuously against any false step. One of the most earnest was Sir Robert Cotton, who made his celebrated " speech at the Council table " in 1651, wherein he points out that " what renown is left to Edward VI. in amending the standard, both in purity and weight . . . must stick as a blemish upon princes that do the contrary. When Henry VIII. had gained so much of power and glory abroad, and of love and obedience at home, as ever any, he suffered shipwreck of all upon this rock ; " and he further observes, " wealth is one essential mark of a kingdom's greatness, and it is best expressed in the measure and purity of the coins ; while kingdoms hold up their glory and greatness they maintain their standards."

From this time we find systematic attempts to render the method of assaying as accurate as possible, and, as an effort in this direction, John Reynolds, Assay Master to King James I., published a series of tables which would afford " a brief and easy way to cast up " the value of silver and gold. A copy of these tables, with corrections by Reynolds, is still preserved in the Mint.

The Assay Masters to King Charles I. appear to have been Andrew Palmer and George Turner, and under the Commonwealth the former name occurs associated with that of Thomas Woodward. In the reign of King Charles II. we come to the name of Mr. Brattle, and with regard to him and to his successors, interesting particulars as to the precise duties of the office, and to the gradually increasing importance attached to it, are gathered from the Record books of the Mint, which, besides showing the terms in which the appointments were made, give various official communications that passed between the Mint Authorities and the Lords Commissioners of the Treasury. A warrant of King Charles II., dated July 12th, 1665, states that Thomas Woodward, Assay Master under the Commonwealth, was then " beyond the seas " . . . " at some plantation in Virginia upon the river called Yorke River," and " knowing of how great a concernment it is . . . to have an able and experienced person in the art of making assays. We have thought fit to appoint Mr. John Brattle, Assay Master." He received the

honour of knighthood, and it is pleasant to remember that Sir John Brattle may have made some of the earliest experiments submitted to our own Royal Society, an account of which was "brought in" to the Society by its first President, Lord Brouncker. Sir John Brattle's name is historically interesting from his connection with the controversy as to whether King Charles I. wrote the celebrated Εἰκὼν βασιλική. He appears to have told Dr. Hollingworth that Bishop Juxon requested his father to edit the work, and declared that he sat up with his father some nights to assist him in methodizing those papers, *all writ in the King's own hand:*" and Dr. Hollingworth adds: "Thanks be to God, Sir John Brattle is still alive and ready to give the same account to any man that asks him." After Charles Gifford, whose name does not appear in Ruding's list, the office was held by Mr. Daniel Brattle, a son of Sir John, who had the good fortune to serve in the Mint at the time Doctor, afterwards Sir Isaac, Newton was Warden. He does not, however, appear to have been altogether free from official troubles, for in 1697 a Committee of the House of Commons was appointed to enquire into the Mint, and its Report contains the following unkind remark: "The Committee doth observe that the present Assay Master and the present Melter of the Tower have married two sisters, and that notwithstanding the last Melter gave up his place as not able to melt the silver at 4 pence per pound weight, and bear all hurt and loss; yet Mr. Ambrose, the present melter, hath got a great estate by his place and keeps his coach," thus suggesting that his gains were not legitimate, and that he would hardly have secured them without the connivance of his relative the Assay Master. I have not been able to ascertain on what evidence this severe stricture was based. Mr. Brattle was succeeded by his brother, Mr. Charles Brattle, whose tenure of office does not demand special comment. Sir Isaac Newton is known to have taken great interest in assaying, and in 1717 he published what has been called a "brief and enigmatic report of critical importance" on the coinage, in which he states that in the end of King William's reign and in the first year of Queen Anne, when foreign coins abounded in England, he caused a number of assays to be made of them, thus affording some data for estimating the relative degree of accuracy attained in the standard fineness of the coins of other countries. It is probable that Newton made some of these assays with his own hands, as a tradition points to his having worked with a particular furnace still preserved in the Mint. Mr. Charles Brattle's successor, Mr. Hopton Haynes, was in many respects a remarkable man; he became well known as a strenuous advocate of Socinian doctrines, and several of his religious treatises were published. He also published a "brief enquiry relating to the right of His Majesty's Royal Chapel, and the privilege of His Servants within the Tower." It appears that in 1728 an attempt was made to treat the church of St. Peter ad Vincula, within the Tower, as if it were a parish church, and, as Mr. Haynes points out, "this bold step does not content them (the claimants), for they have begun to execute writs of Capias and distress within the Tower, which is His Majesty's Royal Castle, with as much temerity as if they had been acting in the dwelling-houses of the meanest subjects." It also appears that one of the officers of the Mint was arrested and threatened with imprisonment in Newgate for resisting the payment of the claims made. Mr. Haynes consequently published, in the form of a memorial addressed to Lord Lonsdale, Constable of the Tower, an elaborate

and learned protest in which he brings to bear every argument, legal, antiquarian, and moral, that could be adduced against admitting the claims, and he incidentally points to the danger of considering the Chapel to be a parish church, because, "In my memory our garrison for many years has been so very slender that the seizing of the Tower might have been not so difficult under colour of a publick wedding or funeral." Mr. Haynes died in 1749, having retired in 1748, when Mr. Joseph Harris was appointed Assay Master by Writ of Privy Seal. The importance of the office appears to have been fully recognised, for the Warden of the Mint makes the following representations to the Lords Justices of Great Britain:—"It would be trifling with their Lordships' time to set forth the nature and importance of the trust of the Assay Office, how the credit and honour of the nation may be essentially affected by the manner of executing it, and how the business is extremely laborious—as these are notorious facts." Mr. Harris was the author of a treatise on "Navigation," and of other scientific papers, as well as of a careful and singularly advanced "Essay on Money and Coins," which proves him to have been a rigid monometallist, as it contains the expression of an opinion that "only one metal can be money, a standard measure of property and commerce, in any country." This essay is specially referred to by Charles, Earl of Liverpool, in his celebrated letter to King George III., dated May 7th, 1805, in which the advantages of a single measure of value, and gold as that measure, are set forth with great vigour and clearness, and this letter has since its publication remained the authority on the subject to which it relates.

In 1764 Mr. Joseph Lucas succeeded Mr. Harris, and in 1789 Mr. Stanesby Alchorne was appointed by Royal Patent. He had entered the Assay Office many years earlier, and was recommended for the post as being "already versed in some parts of chemistry," and as "having shown a very good genius for natural knowledge, qualifications very requisite for an Assay Master." Lord Liverpool, in his letter to the King, already cited, states that "the perfection in the fineness of the gold of which our coins are made is greatly to be attributed to the skill of that excellent officer of the public, the late Mr. Alchorne." He appears, at the request of Lord Cadogan, Master of the Mint, to have made a tour through parts of France and Flanders to inspect the various operations of the several Mints, and to learn "whether any or what improvements might from thence be made in His Majesty's Mint in London." A valuable MS. report preserved in the Mint Library was the result of his investigations, and it is interesting as throwing much light on the nature of the appliances used at the end of the last century. This appears to have been the only official visit to foreign mints, until 1870, when, by the direction of the Lords of the Treasury, the present Deputy-Master of the Mint, the Honourable C. W. Fremantle, C.B., an eminent engineer, Mr. J. Murdoch Napier, and myself visited and reported upon all the principal mints of Europe. Mr. Alchorne retired in 1798, when Lord Effingham reported to the Lords of the Treasury that he was "clearly entitled to every reasonable mark of their Lordships' favour." His successor was Mr. Robert Bingley, recommended to the Lords of the Treasury as being by "study an able chemist." The present coinage of sovereigns and half-sovereigns began in 1817, and nearly sixty million pounds sterling of these new coins were struck during Mr. Bingley's term of office. He retired in 1835, having done valuable

work in pointing out and correcting certain errors to which the operation of assaying gold is liable, and was succeeded by his son, Henry Bingley, who was in turn responsible for the standard fineness of an additional fifty million pounds sterling of gold coin.

In 1851 an important change was effected in the organisation of the Mint, as in that year the system of conducting the operations of coinage by contract was entirely abolished. The Master of the Mint then became absolutely responsible to the Sovereign, and it was no longer necessary to entrust the assays to an officer appointed by Patent from the Crown. Under the Act 5 Geo. IV. cap. 52, which still remains in force, the Queen's Assay Master has, however, statutory duties to perform. The assays of ingots of gold and silver brought into the Mint for coinage were still made within the Mint. On the retirement of Mr. Bingley in 1851, Mr. H. W. Field was appointed Resident Assayer, an office he held for nearly twenty years. He was succeeded by Mr. E. L. J. Ridsdale, who retired in 1882. The verification of the finished coins was in 1851 entrusted to eminent chemists having no office within the Mint, an arrangement which was also for a time in force in the middle of the fourteenth century, the indenture of 1356 providing that the assay of the coin was to be conducted "par deux prud'hommes," not directly connected with the Mint.

In the interval between 1851 and 1870 very distinguished chemists successively received appointments as "Non-resident Assayers;" these were Dr. Hofmann, Professor Graham, afterwards Master of the Mint; Dr. W. Allen Miller, and Dr. Stenhouse, all Fellows of the Royal Society.

Experience in the nineteenth as in the fourteenth century proved that this arrangement was unsatisfactory, and it was abandoned in 1870; the ancient system of conducting the assays of bars and coin within the Mint was again resumed.

The name of one other eminent assayer must also be mentioned, that of the late Professor Stanley Jevons, F.R.S., who was for some years the Assayer in the Sydney branch of the Royal Mint, receiving his appointment when it was first established in 1854. He possessed singular ability and breadth of view, while in addition to his labours in logic and as a statistician his clear and powerful intellect enabled him to bring before the public facts connected with the currency and money in a forcible and interesting way. He moreover may fairly be said to have realised his ideal of life expressed when he was the youthful assayer of the Sydney Mint, "as an absorbing wish that he might be powerfully good—that is, be good not towards one or a dozen or a hundred, but towards the nation." By his premature death in 1882 this country has lost one of its most able servants.

As might have been anticipated, the connection in the past between alchemy and the Mint was very close. Edward III. shut up in a laboratory in the Tower no less an adept than Raymond Lully, in the hope that he would furnish him with gold; and even at the present day samples of precious metal are occasionally brought to the Mint which are alleged to have been produced by transmutation. The survival until quite recent times of traces of alchemy in the Assay Office is very remarkable: the system of handing secrets relating to the precious metals from a master to a chosen disciple survived in the instruction given by the Assay Master to his "probationer," and to him alone, the "mystery" of assaying being jealously guarded by

such devices as employing weights bearing private or unintelligible marks, balances with their mechanism hidden, or by adopting obscure methods of reporting results of assays. Some details of the latter are curious. It was not usual to give the absolute quantities of fine gold or fine silver, but only the relative "fineness"—that is, how much gold or silver the mixture contains, more or less, or "better" and "worse" than the legal standard—thus, in the case of gold of 20 carats fine (or 20 parts of pure gold in 24 parts of the alloy), the assayer put down ℞o. ij. car., and if it was 23 carats 3½ grains fine, he put down ℞r. j. car. iij. gr. ob., the last sign representing an obulus or half-a-carat grain. The close analogy of the "carat and grain" methods of reporting to a medical prescription will be evident at once, for if it were possible for a doctor to prescribe gold and copper, compounded in the proportion of 22-carat gold, he would write :—

℞ Auri ℥ xxij
Cupri ℥ ij
M. Sec. Art.

The occult appearance of the assay report and the prescription with its ℞, the reference to Jupiter, suggests a descent from the time of the early chemists with whom both assaying and therapeutics originated.

The beneficial influence of Alchemy must not, however, be forgotten, for it is certain that chemistry was built up on the knowledge gained in attempting to transmute base metals into gold, and it would be easy to go far towards justifying the claim of a seventeenth-century writer that assaying, by which the purity of gold is determined, "is the very inlet and mother of many other honourable and profitable sciences;" although this is so, every effort has, on the other hand, been made to perfect the art of assaying by the resources of modern science. No one can make an assay of gold without being sensible of the interest of the process; its importance was sufficiently emphasized by the words of King Charles II., who said that the selection of an able Assay Master is a matter of "great concernment," and we find a recognition in 1697 on the part of a Committee of the House of Commons that the office is one of "very great trust."

TRIBUTES TO GRAHAM.

Roberts-Austen's first opportunity of paying public tribute to Graham arose in connection with the inauguration of a Loan Collection of Scientific Apparatus at South Kensington. In 1876 he delivered there a lecture on "The Apparatus employed by the late Mr. Graham, F.R.S., in his Researches,"[1] in the course of which he said :—

"While Faraday was so successfully developing the principles of electrical action, Graham, with equal success, was investigating the laws of molecular motion. Each followed with wonderful constancy, as well as skill, a single line of study from first to last, and to this concentration of power their great discoveries are due. Mr. Graham will probably be best remembered as a chemist, although the most important of his researches were either purely physical or were devoted to the elucidation of questions which occupy an intermediate position between physics and chemistry. Graham's labours were mainly devoted to ascertaining the nature of molecular movement in cases in which he was satisfied that no mass movement could take place; and, as Dr. Angus Smith has pointed out in his Biography of Graham, while Dalton showed the relative weights of the combining quantities, Graham showed the relative magnitude of the groups into which they resolve themselves.

"From the fact that the instruments on the table are those with which he arrived at all his more important conclusions, it will at once be evident that the appliances he used were both few and simple.

* * * * * *

"The story of Graham's work has been much better told by Odling, Williamson, Hofmann, and Angus Smith, but what does it teach us from the point of view of a collection of scientific apparatus? Surely that, although in certain researches or for accurate observation and measurement, delicate and complicated instruments may be necessary, the simplest appliances in the hands of a man of genius may give the most important results. Thus we have seen that, with a glass tube and a plug of plaster of Paris, Mr. Graham discovered and verified the law of diffusion of gases. With a tobacco pipe he proved indisputably that air is a mechanical mixture of its constituent gases. With a tambourine and a basin of water he divided bodies into crystalloids and colloids, and obtained rock crystal and red oxide of iron soluble in water. With a child's india-rubber balloon filled with carbonic acid he separated oxygen from atmospheric air, and established points, the importance of which, from a physiological point of view, it is impossible to overrate."

In 1877 Roberts-Austen reviewed the Memorial Volume of Graham's *Chemical and Physical Researches*,[2] which had been prepared by Dr. Angus Smith and Graham's life-long friend, Mr. James Young, F.R.S. Two years later (1879) the Chemical Section of the Philosophical Society of Glasgow instituted a scheme of triennial lectures in commemoration

[1] *Nature*, vol. xiv., 1876, p. 511.
[2] *Nature*, vol. xv., 1877.

of Graham's work. For the inauguration of this scheme, Roberts-Austen was invited by the Society (of which Dr. (now Sir) William Ramsay was then Secretary) to deliver the first lecture. The subject selected was "Molecular Mobility or some Forms of Invisible Motion." Mr. James Young, F.R.S., presided. Roberts-Austen briefly traced the influence of Black and Thomson in turning the attention of Graham to the study of molecular physics, and then reviewed the researches which dealt more especially with "molecular movement," showing their influence on subsequent thought and work. In conclusion, he spoke of the lectures as having been instituted "in honour of the patient labours of a life, the memory of which will be as enduring as its work, and to stimulate others to investigate as patiently and earnestly the varied phenomena whose basis is 'molecular mobility.'"

Twenty years later (1900) he was again invited by the Philosophical Society of Glasgow to deliver the "Graham Lecture." Under the title of "Molecular Unrest in Solids," he traced the effect of Graham's teaching in relation to certain branches of scientific work. Graham's classical work on the diffusion of salts and Roberts-Austen's work on the diffusion of metals both formed the subjects of Bakerian Lectures before the Royal Society—Graham's in 1849, and Roberts-Austen's in 1896.

A reference to these tributes will show how deep was his admiration for Graham, while his own work shows how much he owed to him. Perhaps the most striking aptitude which is traceable to Graham's influence is the remarkable facility with which he adapted simple means to important ends.

III.

THE ROYAL SCHOOL OF MINES.

Association with the School of Mines—Appointed to the Chair of Metallurgy—Text-book on Metallurgy—Introductory Lecture to the Course of Metallurgy—Address on the Development of Technical Instruction in Metallurgy—Address to the Chemical Section of the British Association—Tribute to Dr. John Percy.

ROBERTS-AUSTEN'S association with the Royal School of Mines began, as a student, in 1861, ten years after its establishment at Jermyn Street. He completed the course, taking the Associateship in Metallurgy, in 1863. Very shortly afterwards he went to the Mint as a private assistant to Graham and continued to assist him in his researches until his death in 1869.

Roberts-Austen was always a "School of Mines man" in the fullest sense, loyal to its teachers and anxious always to enhance its good name.

It would be out of place in this record to attempt to give an historical account of the growth of the School, except in so far as Roberts-Austen was concerned in helping on its work and building up its reputation.

The foundation of the School, as a part of the Geological Survey of Great Britain (which had been established under the direction of Sir Henry de la Beche in 1832), and its development through many changes and vicissitudes, have been admirably traced by Mr. Theodore Chambers in a preface to the Register of Associates and Old Students, compiled by him in 1896.[1]

It is of interest, however, to recall the names of those under whom Roberts-Austen studied at Jermyn Street. The School of Mines was then under the direction of Sir Roderick Murchison, while the Chairs of Metallurgy and of Mining had been occupied respectively by Percy and Warington Smyth since 1851. The Chair of Biology was occupied by Huxley, those of Chemistry and Physics by Hofmann and Tyndall, Geology by Andrew C. Ramsay, and Mechanics and Mathematics by Robert Willis.

Seventeen years elapsed from the time Roberts-Austen left the School in 1863 before he again became directly associated with it. During this period his reputation had been steadily growing in consequence of his numerous activities arising out of his connection with the Mint, where, after the death of Graham, his position had changed from one of private capacity to one of official importance (see p. 4).

His scientific work had received recognition in 1875, when, at the early age of 32, he was elected a Fellow of the Royal Society, while his ability as a lecturer had manifested itself in his tributes to Graham, to which reference has been made (pp. 76 and 77).

His success, both as a worker in the laboratory and as a lecturer in public,

[1] Hazell, Watson & Viney, 1896.

The Museum of Practical Geology, Jermyn Street (originally the Royal School of Mines).

led, no doubt, to the invitation which he received in 1880, from the Lord President of the Council, to occupy the Chair of Metallurgy at South Kensington when that branch of the work of the Royal School of Mines was about to be removed from Jermyn Street.

The circumstances surrounding this removal mark, in many ways, the breaking of old ties in the School. Dr. Percy, who had occupied the Chair from its establishment in 1851, regarded with grave concern the removal of the instruction in Metallurgy to South Kensington, although this course had been recommended by a Royal Commission ten years previously (1873), with regard to the whole School. The recommendations of the Commission had been carried out so far as certain subjects were concerned (Chemistry, Physics, Applied Mechanics, Biology, and later—1876—Geology); but the instruction in Mining, Metallurgy, and Mineralogy, constituting the identity of the Royal School of Mines, had continued at Jermyn Street.

Difficulties in connection with the lease of premises occupied by the Metallurgical Laboratory and also the inadequate accommodation obtainable, led to the proposed transference to South Kensington in 1879. This proposal met with strong opposition from Dr. Percy, who even offered to build a laboratory on the site of the existing one at his own expense. The authorities were determined, however, sooner or later, to concentrate the School of Mines at South Kensington, and even had his generous offer been accepted by the Government, the removal would probably have taken place before long.

It was under these somewhat clouded circumstances that Percy regretfully decided to sever his long connection with the School and towards the latter end of 1879 he resigned his position. .

Roberts-Austen was appointed to the vacant Lectureship on the 7th of May, 1880, by the Committee of Council on Education, the appointment being sanctioned by the Lords Commissioners of the Treasury, and made by them conditional on the continued discharge of his duties at the Mint.

Roberts-Austen delivered his introductory lecture to the students of the course of Metallurgy in 1880. This has been thought of sufficient value to reproduce in full (see pp. 84-98). It foreshadowed the line of work which occupied his attention during the following twenty years—the effect of traces of impurities on masses of metal, the molecular constitution and structure of metals and alloys, and the consideration and measurement of high temperatures.

In order to realize more clearly the condition in which Roberts-Austen found the organisation for technical education at the time of his appointment, it will be necessary to consider briefly the events of the few years preceding it.

For some time, the Government, and those responsible for the provision of scientific teaching, had been somewhat restricted in their actions by questions of expediency. On the one hand, it was agreed that the School of Mines should be maintained as an Institution intended, in the words of the Prince Consort in 1851, "to direct the researches of science and to apply their results to the development of the immense mineral riches granted by the bounty of Providence to our Isles and their numerous colonial dependencies."

On the other hand, for thirteen years various schemes had been under consideration for establishing a general College of Science for the training

of those who were to teach the methods of science throughout the country. All these schemes had involved the idea that such a College should necessarily arise from the extension of those courses of lectures delivered at the Royal School of Mines which dealt with matters which were of a general scientific character rather than of particular concern to students of Mining and Metallurgy.

A Select Committee of the House of Commons had been appointed in 1868 to consider the question. The counsels of expediency, referred to already, had their origin, of course, in the question of expense.

The whole argument in favour of making use of the existing facilities of the Royal School of Mines in establishing an institution for general scientific instruction lay in the contention that the comparatively small number of students trained there did not appear to justify the expense of the School to the nation. Professor Huxley contested this point with considerable vigour.

In 1870 a Royal Commission had been appointed to reconsider the whole question for the guidance of another Government, but their recommendations were not put into effect. Ten years later, however (1880), their proposals were embodied in a Memorandum issued by the direction of the Lords of the Committee of Council on Education, through the channel of the Science and Art Department which, during the period which had elapsed, had gathered to itself considerable power in controlling affairs.

This Memorandum was circulated among the Professors of the School of Mines, who were invited to express their views with regard to the proposals it contained. Huxley's recorded opinion of it lacks the enthusiasm of conviction. He regarded it as being "just and expedient." Roberts-Austen's views are embodied in his reply, from which the following paragraphs have been taken :—

ROBERTS AUSTEN'S OBSERVATIONS ON THE MEMORANDUM RELATIVE TO THE ROYAL SCHOOL OF MINES AND THE SCIENCE SCHOOLS, SOUTH KENSINGTON (8th January, 1881).

"I believe that the scheme, while providing for a comprehensive system of science teaching, will, at the same time, be advantageous to students who are preparing for a career in connection with the great mineral industries.

"The prospectus of the School of Mines has for the last twenty years pointed out that 'the principal object of the Institution is to discipline the students thoroughly in the principles of those sciences on which the operations of the miner and the metallurgist depend.' I venture to think that these words indicate the basis of any system for concentrating and strengthening the teaching.

"Metallurgy is specifically separated in the Memorandum from those subjects recognised as 'matters of general science,' but I would submit that the intimate connection between Mining and Metallurgy, hardly indicated by the restrictive name 'School of Mines,' is not made more evident. The Memorandum points to a certain degree of isolation of Mining in 'a special School of Mines in Jermyn Street,' and I fear that, if safeguards are not provided to preserve the true character of the School as, so to speak, a 'School of Metals,' the Mining Student will be tempted to reduce to the narrowest limits, or even to neglect, the study of Metallurgy, a thorough knowledge

Plate VI.]

[*To face page* 81.

The Royal College of Science and Royal School of Mines (until 1912).

of which cannot fail to be of very great importance to him, and is, in most cases, essential to success.

"On the other hand, the teaching of Metallurgy in the proposed College of Science at South Kensington will, I am satisfied, prove of great value to the country, as it will be possible, by training science teachers, to provide for the scientific instruction of blast-furnace managers and foremen in metallurgical works. These so-called practical men hold positions which, though subordinate, often involve great responsibility, and I need not allude to the vital importance of such teaching in this country with its vast mineral interests.

"These and similar considerations lead me to prefer the scheme which involves the removal of the whole establishment, now in Jermyn Street, to South Kensington."

It was under these conditions that Roberts-Austen began his work as the Professor of Metallurgy at South Kensington, the Chair of Mining remaining at Jermyn Street until the death of Sir Warington Smyth in 1891, when the connection with Jermyn Street was finally severed, and his successor, Mr. (afterwards Sir) Clement Le Neve Foster, commenced his work at South Kensington.

The eminence attained by the distinguished colleagues with whom Roberts-Austen was associated during the twenty-two years of his Professorship renders it unnecessary to do more than refer to them by name.

Huxley became the Dean in 1881, and continued to direct the affairs of the Royal School of Mines and Royal College of Science until his death in 1895. He was succeeded by Judd, who had occupied the Chair of Geology since 1876. Warington Smyth completed forty years as Professor of Mining in 1891, and was succeeded by Le Neve Foster. Frankland occupied the Chair of Chemistry until 1885, and was succeeded by Thorpe, who was in turn succeeded by Tilden in 1894. Guthrie occupied the Chair of Physics until 1886, and was succeeded by Rücker. Goodeve was succeeded in the Chair of Mechanics and Mathematics by Perry in 1895. Norman Lockyer, who had previously been associated with Roberts-Austen in important researches, was appointed to the Chair of Astronomical Physics contemporaneously with Roberts-Austen's appointment to the Chair of Metallurgy in 1881.

During the early years of his Professorship, Roberts-Austen was actively engaged in co-operation with the Science and Art Department in organising the teaching of Metallurgy throughout the country, and as the Examiner in Metallurgy under the Department he had considerable influence in the guidance of metallurgical teaching in accordance with his own views and methods. An opportunity for expressing his views was afforded at the opening of a new School of Metallurgy in Birmingham (1885), at which he presided and delivered an Address on the "Development of Technical Instruction in Metallurgy." This is reproduced on pp. 99-105.

In 1891 the first edition of his text-book for metallurgical students was published under the title of *An Introduction to the Study of Metallurgy*. This volume quickly acquired a world-wide reputation, and was followed by later editions, each growing in bulk and usefulness, the Fifth Edition being published just before his death.

The lines which have already been quoted in the introductory paragraphs to this volume and which appeared opposite the title page of the book may be taken as the expression of what he had attempted to achieve by placing this work in the hands of his students.

"I rather open, than discover things."
— *Montaigne's Essays* (1580).

"No doctrine of any importance can be transferred in a matured shape into any man's understanding from without: it must arise by an act of genesis within the understanding itself." —*De Quincey* (1823).

"To know
Rather consists in opening out a way
Whence the imprisoned splendour may escape,
Than in effecting entry for a light
Supposed to be without." —*Browning's "Paracelsus"* (1835).

An expression of his views on the teaching of metallurgy was given in the Preface to the First Edition. Portions of this Preface may be quoted.

"The literature of metallurgy is rich, but those who are beginning to study it need guidance to a knowledge of the principles on which the art is rightly practised. It depends, as is well known, on the application of chemistry, physics, and mechanics; but the methods of metallurgists vary greatly from those of chemists, who, however, frequently fail to appreciate the nature of the difference.

"Ten years experience has convinced me that it is more important at the outset for the student to know what was the scope of mind of the early practisers of metallurgy, and to see what kind of aid the art may be expected to receive in future from the sciences, than to acquire familiarity with complicated details of processes and appliances. In this little volume I have, therefore, devoted four chapters to these branches of the subject, embodying in them portions of lectures which I have delivered from time to time.

"In all English works on metallurgy, the important metals are dealt with separately and in detail. In this, however, an attempt has been made to treat the subject as a whole, giving no minute descriptions of processes, but choosing typical appliances and indicating their use in connection with groups of metals. Such a method was adopted by the late M. Gruner, Professor of Metallurgy at the Ecole des Mines, Paris, to whom I have reason to be grateful, for I have closely followed him in my class lectures."

The First Edition was very favourably received by those best fitted to judge of its merits, and a few lines may, perhaps, be quoted from a review which appeared in *Nature* (9th April, 1891), as it aptly summarises the most salient features.

"There has been a distinct want of a systematic exposition of the general principles of metallurgy and of clear statements as to the physical characters of metals and alloys. These are more especially needed by students on the threshold of metallurgy who desire to enter profitably on the study of the more or less disconnected details of the art as applied to the several metals, such as are to be found in special monographs. The evident purpose of the volume is to meet this want, the author having deliberately subordinated

details of smelting operations in order that he might deal at length with the physical properties of metals and the constitution and characters of alloys, modified as these properties often are by thermal treatment and the presence of small quantities of foreign elements. Such questions are treated with much wealth of research and abundant reference to authority. The book will hardly be popular with the class of students who merely attempt to 'cram.'"

In the last remark made by the reviewer, he has drawn attention to one of the chief merits of this notable book. It was essentially, as its title was intended to convey, an introduction to the *study* of metallurgy.

The publication of this volume by Messrs. Charles Griffin & Co. was the inauguration of a series of metallurgical treatises written by distinguished men who were Associates of the Royal School of Mines. Roberts-Austen's name appeared as the Editor of this series of works, in the production of which he took an active interest. The distinction attained by these treatises is too well known to need comment.

In the capacity of a lecturer and expositor Roberts-Austen addressed himself not only to students, but also to all classes of scientific and technical men. He lost no opportunity of dwelling on the importance of metallurgical science. His vivid imagination furnished him with illustrations which invariably had the effect of arresting attention. On one occasion he said—

"If the thousands of tons of steel in the Forth Bridge had contained two-tenths per cent. less of carbon the material would have been worthless. Thousands of tons of copper would be useless if it contained a trace of bismuth. Millions of sterling gold coin would have crumbled away if it had contained one-tenth per cent. of lead."

A distinguished colleague (Sir Edward Thorpe) has said of him as a lecturer—"Perhaps no man since Tyndall's day ever handled a Friday Evening Discourse at the Royal Institution with more tact and skill than did Roberts-Austen. His matter was always fresh, his experiments always interesting, frequently daring, and strikingly original. He never tried to be rhetorical or pretended to be eloquent, but there was a certain literary finish in his sayings, a feeling for epigram, a sense of proportion in arrangement, and at times a quiet, subdued touch of humour which altogether made him delightful to listen to."

The general addresses, which in this volume have been given the prominence which is due to them, testify amply to the breadth of his interests and the wide extent of his influence. Those which have been chosen for inclusion in this section of the volume are Addresses which may be said to fall within the scope of his work as a Professor of Metallurgy, and they will be found to embody his views on the teaching and training of metallurgists.

His Addresses as President of the Iron and Steel Institute, his Friday evening lectures at the Royal Institution, and his lectures to the Royal Society of Arts on Alloys and Art Metal Work are dealt with in other sections.

METALLURGY IN ITS RELATIONS TO CHEMICAL SCIENCE.

Introductory Lecture to the Course of Metallurgy at the Royal School of Mines, Session 1880-81.

The distinguished metallurgist who has held this lectureship since the foundation of the Royal School of Mines, concluded the introductory lecture he delivered more than a quarter of a century ago [1] by pointing out, to the students who were then beginning their course, that "in proportion to the success with which the metallurgic art is practised in this country, will the interests of the whole population, directly or indirectly, in no inconsiderable degree be promoted." This is a fact that none of his students are likely to forget.

Looking back on the actual advance of this country during the past thirty years, and remembering that the success with which any manufacturing art is practised must bear a direct relation to the way in which it is taught, we cannot but feel how greatly this development of metallurgical knowledge must have been influenced by Dr. Percy's labours. During this period the conditions under which metallurgy is practised have changed considerably; for the field of knowledge has so widely extended, the scale on which operations are conducted is now so great, and the mechanical appliances they involve are so varied and complicated, that while the interest of our subject is deepened its difficulty is gravely increased.

On the other hand, the preliminary training of the students before entering the school has much improved, although it still falls short of that required on the Continent—in France, for instance, where admission to the higher mining schools, such as the Ecole des Mines, is only granted to those who have either passed through the Ecole Polytechnique, graduated in science, or have passed a rigorous examination. While not advocating a too comprehensive preliminary training, I am none the less glad to see from the class lists that I am fortunate in having to lecture to students, many of whom have already distinguished themselves in chemistry, physics, and mechanics.

In turning to the history of metallurgy, more especially in its relation to chemical science, it is easy to be led away by the charm of the antiquarian riches of our subject into devoting too much time to this kind of literary research; I may remind you, however, that much of what is both interesting and full of suggestion, even at the present day, is to be found buried in the treatises by the old writers whose work we inherit and continue.

Primitive metallurgical processes are referred to in some of the oldest known historical records; naturally, therefore, the development of metallurgy as a science must have been long preceded by its practice as an art, an art for which a place has even been claimed among the religious systems of antiquity.[2] The earlier literature of the subject consists mainly of descriptions of processes; but it is well known that chemistry was to a great extent

[1] *Records of the School of Mines*, vol. i. pt. 1 (1852), p. 127.

[2] Rossignol, "Les métaux dans l'antiquité" (1863).

built up on a metallurgic basis, and Black's singularly advanced definition of Chemistry as the "effects produced by heat and mixture"[1] might well be applied to Metallurgy. The library of Leyden contains a papyrus which has been described by M. Reuvens,[2] and is considered by Kopp[3] to be the oldest known chemical MS., its date being possibly as early as A.D. 200. It treats generally of metallurgical matters, and the purification of gold and silver is frequently mentioned. But of all the phenomena of our subject, probably none have more contributed to advance the science of chemistry than those bearing upon the relations between oxygen and lead; indeed, the interest attaching to the mutual behaviour of these two elements is so great that I propose devoting a few minutes to its consideration, more especially as I am anxious to indicate the influence of an ancient process on the scientific views of the present day.

When lead is melted with free access of air, a readily fusible substance forms on its surface. This substance may be allowed to flow away, or, if the metal is contained in a suitable porous receptacle, the fusible oxide sinks into this containing vessel; in either case the oxidation of the lead affords a means of separating it from precious or inoxidisable metals if any were originally present in the lead. The above fact has been known from remote antiquity, and the early Jewish writers allude to it as old and well known. They clearly show, for instance, that lead can be removed from silver by being "consumed of the fire," while the silver is not affected. That the Greeks knew and practised the method is abundantly proved, if only by certain specimens of gold and silver now in the adjoining museum, which were recently discovered by Dr. Schliemann. The Arabians investigated the subject; for passing to Geber,[4] the greatest of the early chemists (he died in 777), we find a remarkable account of cupellation; he also describes the conversion of lead into a fine powder by calcination with much clearness, and he noticed the fact that after calcination the mass has "acquired a new weight in the operation." I think his subsequent observations on the reduction of altered metals from their "calxes" show that he knew the weight to be increased; in any case it is interesting to remember that his work was, in a sense, quantitative. He, moreover, was cognisant of the fact that two different substances may be produced by heating lead in air, and he assumed that "in the fire of calcination a fugitive and inflammable substance is abolished." The alchemists refer continually to the subject, and "deliver themselves," as Roger Bacon said, in his "Speculum Alchimæ," "in the enigmas and riddles with which they clouded and left shadowed to us the most noble science." In the middle of the sixteenth century the truly accomplished metallurgist Biringuccio,[5] contemporary of Paracelsus and Agricola, seems to have been specially attracted by the phenomenon in question, and he remarks:—"If we had not lead we should work in vain for the precious metals, for without its aid we could not extract gold or silver from the stones containing them. . . . The alchemists also," he said,

[1] Lectures by Joseph Black, M.D., vol. i., p. 8 (Edin. 1803).

[2] Reuvens, "Lettres à M. Letronne" (Leide, 1830), quoted by Prof. Ferguson in an address to the Glasgow Phil. Soc. (1876), p. 19.

[3] Beiträge zur Geschichte der Chemie, 1869.

[4] The Works of Geber, translated by R. Russell (1686), pp. 74, 78, 220, 234.

[5] Pirotechnia (Vinegia, 1540), translated into French by T. Vincent (Rouen, 1627), p. 41.

" make use of it in their operations, calcining it by itself or with other substances; but," he goes on to observe, " the calcination, conducted in a reverberatory furnace is accompanied by a marvellous effect, the result of which should not be passed by in silence; for lead thus treated increases ten per cent. in weight, and, considering that most things are consumed in the fire, it is remarkable that the weight of lead is increased and not diminished." Although he subsequently gives evidence of much accurate knowledge of practical metallurgy, his views as to this particular phenomenon were hardly in advance of Geber's; but we may claim Biringuccio as an early metallurgist, who knew the facts, and recognised that they were theoretically important. It was not until nearly a century later (1630) that a French chemist, Jean Rey,[1] stated that the increase in weight came from the air. The problem attracted much attention in England; and it is not a little interesting that among the very first experiments recorded by our own Royal Society is a metallurgical series relating to the weight of lead increased in the fire on the " copels " at the assay office in the Tower, the account being brought in by Lord Brouncker in February, 1661.[2] Subsequently, in 1669, John Mayo showed that the increase in weight of calcined metals was due to a " spiritus " from the air.[3] Boyle heated lead in a small retort,[4] and attributed the increase in weight, as Lemery also did,[5] to his having arrested and weighed igneous corpuscles." [6]

I need hardly point out how important this calcination of lead was considered by those who defended the Phlogistic theory in regard to chemical change, a theory which, for more than a century, exerted so profound an influence on scientific thought; as, however, we owe it to a metallurgist, Becher, I cannot dismiss it without a few words. (Here is the book in which his views were first embodied, the *Physica Subterranea* (1669), and here is his other celebrated work, the *Alphabethum Minerale* (1682).

According to his still more famous pupil Stahl, the litharge produced by the prolonged calcination of lead in air is lead deprived of its phlogiston; but he and his followers were indifferent to the fact that when lead is burnt the weight of the resulting mass is greater than that of the original metal, and were content to insist that the burnt lead had lost its inflammable principle—that is, Phlogiston. Lavoisier, as we know, overthrew the old phlogistic theory by showing that a chemical combination takes place, resulting in

[1] Essays de Jean Rey (reprinted in Paris, 1777), p. 64.

[2] MS. Register Book of the Royal Society.

[3] Tractatus quinque Medico-Physici, p. 25, *et seq.* (Oxonii, 1674).

[4] Collected works, vol. iii. (1744), p. 347.

[5] Cours de Chymie (1675), 2nd English edition (1686), p. 107.

[6] I am indebted to my friend, Prof. Ferguson, M.A., of the University of Glasgow, whose eminence as a historian of Chemistry is well known, for several interesting additional facts in connection with the calcination of metals. After referring to Eck (1489), Glauber (1651), and others, he writes:—" One of the most curious passages I know is in the " Hippocrates Chemicus " of Otto Tachen, or Tachenius, a German who lived at Venice and published his book there in 1666. He describes how lead, when burnt to minium, increases in weight. This increase he ascribes to a substance of acid character in the wood used for burning, and then, by a very curious course of argument, based on the saponifying powers of litharge, makes out that lead is of the nature of or contains an alkali, which combines with the " occult acid of the fat." This is a curious anticipation of a very modern classification which brings lead into relationship with the alkalies and alkaline earths, as well as of Chevreul's investigations."

an augmentation of weight which represents the exact weight of the gaseous body added. At the same time it should be remembered that the phlogistic chemists made a great step in advance, as was admitted by J. R. Mayer in his memoir on the mechanical theory of heat [1]; and Odling, discussing the experiments on the oxidation of lead, has more recently pointed out [2] that an error has arisen in consequence of the same word being used in a different sense at different periods of time: chemists, in fact, now substitute the words potential energy for phlogiston; or, as Dr. Crum-Brown has well observed,[3] we recognise "that no compound contains the substances from which it was produced, but that it contains them *minus* something. We now know what this something is, and can give it the more appropriate name of potential energy; but there can be no doubt that this is what the chemists of the seventeenth century meant when they spoke of phlogiston." It will thus be evident that the main aim of chemical investigation down to the end of the last century was the explanation of calcination, combustion or oxidation, and that lead was specially useful in solving the problem.

I might, perhaps, add that the *absorption* of oxygen by molten litharge has furnished M. Ste. Claire Deville,[4] a physicist and metallurgist, with an important step in the argument as to dissociation, and thus connects the history of the metal with the great advance on the borderland of chemistry and physics in modern times, to which I shall constantly refer.

The above remarks will, I trust, be sufficient to show that conclusions of the utmost importance in the history of chemical theory were based on a very ancient metallurgical process; but I have also selected lead as an illustration, because, in the gradual development of the knowledge derived in the first instance from its metallurgy, there is much that is typical of the mutual relation of theory and practice that still prevails.

When Dr. Percy began his teaching, he considered at some length the kind of assistance that other sciences might be expected to render our subject, considered as a manufacturing art; and this at the time was necessary for two reasons: [5] first, because he was "able to adduce from his own observation several striking cases in illustration of the advantage of the application of science to practical metallurgy; and, second, because the practice of metallurgy, so far as relates to magnitude of operation, having been developed to an unparalleled extent in this country in the absence of specific public instruction on the subject, it was necessary to justify the providing of such instruction."

The absence of accurate knowledge on the part of those engaged in metallurgy was lamented as long ago as 1700, in an "Inaugural Dissertation of Pyrotechnical Metallurgy," delivered, on the 25th of March of that year, in the University of Magdeburg; no less a person than the great supporter of the theory of phlogiston, George Ernest Stahl, presided, and the lecturer was Fritschius, who said: [6]—"If in any part of the working of metals there

[1] "Bemerkungen über die Kräfte der unbelebten Natur," *Liebig's Ann.*, xlii., p. 233, 1842.

[2] *Proc. Roy. Inst.*, vol. vi., p. 323, 1871.

[3] *Edin. Roy. Soc. Proc.*, v., p. 328, 1866.

[4] Leçons sur la Dissociation, 1864.

[5] *Records of the School of Mines*, vol. i., pt. 1, p. 128, 1852.

[6] Pyrotechnical Metallurgy, by J. C. Fritschius of Schwartsburg (translated in 1704), p. 203.

is commonly more owing to experience than reason, truly it is in fusion or melting . . . nevertheless if the reason be asked why the business succeedeth well in this way, but in another doth not succeed at all, you have no solid answer, but only that most general one, which is most commonly false, viz., that one fire is stronger and another weaker, and so insufficient." It is just a century since Bishop Watson, Professor of Chemistry and Regius Professor of Divinity in the University of Cambridge, pointed out [1] that "the improvement of metallurgy and other mechanic arts dependent on chemistry, might best be made by public establishment of an Academy, the labours of which should be destined to that particular purpose"; and the School of Mines, thus foreshadowed, was established in 1851, its principal object being to "discipline the students thoroughly in the principles of those sciences upon which the operations of the miner and metallurgist depend."

Our honoured founder, Sir Henry de la Beche, in his Address at the opening of the School of Mines,[2] said:—"We still too frequently hear of practical knowledge, as if in a certain sense opposed to a scientific method of accounting for it, and as if experience, without that advantage, was more trustworthy than the like experience with it." Such remarks might, with truth, be made at the present day; but it should nevertheless be remembered that many metallurgical works are successfully conducted in this country by so-called practical men. I do not mean the kind of man so forcibly described by Mr. Bramwell [3] as one "whose wisdom consists in standing by, seeing, but not investigating, the new discoveries which are taking place around him. . . . the aim and object of such a man being to ensure that he should never make a mistake by embarking his capital or his time in that which has not been proved by men of large hearts and large intelligence"; nor do I mean the man who accepts no rule but the rule of thumb; but I do mean practical men possessing technical knowledge of a high order, whose careful observation enables them to use the results of past experience in dealing with circumstances and conditions analogous to those they have met with before, and with which long practice has made them familiar. It would be difficult to overrate the value and importance of such knowledge as theirs, and, when we remember the scale on which smelting and other operations are carried on, it will be obvious that this kind of knowledge can only be gained in the works, and not in the laboratory or lecture-room; for, however careful the metallurgical teaching here may be, it can only be practical in a limited sense. At the same time it must be borne in mind that a man trained to scientific methods starts with the enormous advantage of being able to deal with circumstances and conditions that are new to him, and with which, therefore, he cannot be said to be "familiar." The technical skill that time and opportunity can alone give him will then rest on a solid basis. I repeat, however, that I am anxious at the outset to guard against undervaluing the teaching of experience unaided by reasoning that we should recognise as scientific; for it is only necessary to witness such operations as the roasting of a large mass of ore on the bed of a furnace, or the forging of many tons of iron under a steam-hammer, to appreciate the value of the subtle skill of sight and touch on which success depends.

[1] Chemical Essays, 2nd edition (1782), vol. i., p. 47.
[2] *Records of the School of Mines*, vol. i., pt. 1, p. 20, 1852.
[3] *British Association Report*, Brighton (1872), p. 238.

I have thus ventured to trace the relation between scientific and technical men, as hitherto there have been misunderstandings on both sides, or, as Dr. Williamson so well observes:[1]—"Men of detail do not sufficiently appreciate the value and usefulness of ideas, or of general principles: and men of science, who learn to understand and control things more and more by the aid of the laws of nature, are apt to expect that all improvements will result from the development and extension of their scientific methods of research, and not to do justice to the empirical considerations of practical expediency, which are so essential to the realisation of industrial success in the imperfect state of our scientific knowledge."

While it is no longer necessary to justify the scientific teaching of metallurgy, as Dr. Percy did, it is as important as ever that the true relation of Theory and Practice should be clearly understood. It rarely happens that a process can be transferred from the laboratory to the works without important modifications; and we must remember that metallurgy is a manufacturing art, and that, when the truth of a theory has been demonstrated, a dividend has to be earned; this would indeed often be difficult without the aid of the technical man. Practical men have, however, ceased to undervalue science; and the most practical body of men in the world, in the best sense of the term, the Iron-masters of this country, on whom its prosperity so largely depends, formed themselves ten years ago into an Iron and Steel Institute, many of the members of which possess high scientific attainments and are distinguished for scientific research.

Let us turn, then, to the advice given us by those who are accustomed to deal with metals on a large scale. Mr. I. Lowthian Bell stated in his address as President of the Institute in 1873:[2]—"If we would avoid the failure of what may be designated unscientific practice, or the failure of impracticable science, we must seek to combine commercial intelligence with a knowledge of those natural laws which form the only trustworthy groundwork of the complicated processes in which we are engaged."

Dr. Siemens[3] said in 1877:—"It is not many years since *practical* knowledge was regarded as the one thing requisite in an iron-smelter, whilst *theoretical* knowledge of the chemical and mechanical principles involved in the operations was viewed with considerable suspicion;" and he adds, with reference to the teaching of the School of Mines and of a general Technical University:—"But it must not be supposed that I would advocate any attempt at comprising in its curriculum a practical working of the processes which the student would have to direct in after-life. . . . Let technical schools confine themselves to teaching those natural sciences which bear upon practice, but let practice itself be taught in the workshop and in the metallurgical establishment."

The President for 1879, Mr. E. Williams, a most eminently practical man, and one of the founders of the prosperity of the great Cleveland iron district, urged[4] "educated intellectual young men, who now hang listlessly about the professions, . . . to break through the absurd old prejudice against seemingly rough work," in order that they may act as scientifically trained managers.

[1] "A Plea for Pure Science" (Inaugural Lecture, University College, London, 1870).
[2] *Journ. of the Iron and Steel Inst.* (1873), No. 1, p. 12.
[3] *Ibid.* (1877), No. 1, p. 7.
[4] *Ibid.* (1879), No. 1, p. 24.

I have thus appealed to authorities, because my own practical work has been mainly confined to a limited branch of metallurgy; but I am none the less convinced that in metallurgical works generally, as in a Mint, the work can only be efficiently conducted by taking advantage to the utmost extent of the aid that science has to offer, a Mint only differing from other works by the extraordinary care and vigilance which must be exercised to ensure accuracy and avoid loss in dealing with the precious metals. Even this difference is less marked than formerly, and, as attention to minute details is becoming more and more essential to the profitable conduct of works, my experience in this respect will be useful to you.

On the Continent, as is well known, the Government Inspectors and Engineers are far more numerous than in this country, where both the extraction and utilisation of metals are left largely to private enterprise. One result of this official influence is that it enables students in the mining schools to visit and report on works as part of their educational course. I hope that it may be possible to arrange for systematic visits of students to manufactories in this country. I have already received courteous promises of aid from several owners, and the wide distribution of our own men throughout the country will doubtless help to render this easy.

As regards the actual training in the school, I believe that our utmost efforts should be devoted to giving the students a thorough acquaintance with scientific methods and metallurgical principles, furnishing them at the same time with as many well-ascertained *facts* as possible. Here I may, perhaps, be permitted to quote a few words from Prof. Huxley's [1] address at Birmingham on Friday, as they bear so directly on our subject; he said, "What people call applied science is nothing but the application of pure science to particular classes of problems. It consists of deductions from those general principles, established by reasoning and observation, which constitute pure science. No one can safely make these deductions until he has a firm grasp of the principles; and he can obtain that grasp only by personal experience of the processes of observation and of reasoning on which they are founded."

In one important branch of metallurgy—assaying—the teaching in the School is thoroughly practical, and the operations you may in future be called upon to conduct will not differ from those taught in this laboratory. The teaching will, I am glad to say, be now specially entrusted to my friend Mr. Smith,[2] the value of whose instruction, in my own case, I gratefully acknowledge.

It can hardly be questioned that, until the School of Mines was established, the metallurgical success and reputation of this country rested to a remarkable extent on the exceptional skill of its technical men. I think, therefore, we may fairly be asked to consider whether the metallurgical teaching of the School has been justified, and how far advance has been due to trained scientific thought.

Of all the metallurgical operations conducted in this country, those connected with iron are, of course, the most important. The production of pig-iron alone in the United Kingdom has increased from 2,700,000

[1] *The Times*, October 2, 1880.

[2] Mr. Richard Smith was for many years the Instructor in Assaying at the Royal School of Mines.

tons in 1852 to 6,200,000 tons last year, a maximum slightly in excess of this figure having been reached in the year 1872. Now the Bessemer process, the first patent in connection with which was taken out in 1855, has reduced the cost of steel from £50 to £6 per ton, and has changed the whole aspect of the iron and steel manufacture; indeed, the success with which this process alone is conducted may almost be regarded as an index of our national prosperity. Notwithstanding the almost universal depression of trade during the last few years, the outturn of steel has been steadily increasing; and it is estimated that in 1879 this country produced nearly a million tons in the Bessemer converter, double the entire produce of the remainder of the world in the year 1870 by the same process.[1] The outturn of Bessemer steel in America has, however, advanced with still more rapid strides; for last year she actually produced, with far fewer converters, 94,000 tons more than this country. It will be evident, therefore, that every improvement effected in this process is of truly national importance, and I would briefly refer to the greatest that has been introduced in recent years.

In 1855 the fact was established that pig-iron from the blast furnace contains the greater part of the phosphorus originally present in the ore. Dr. Percy pointed out that phosphorus is not eliminated in a sensible degree in the Bessemer process, as it is in the old process of puddling; and he stated that if the Bessemer process is to be "generally applicable in this country, it must be supplemented by the discovery of a process of producing pig-iron sensibly free from sulphur and phosphorus, with the fuel and ores which are now so extensively employed in our blast furnaces."[2] The problem, so far as it relates to the elimination of phosphorus, has received the attention of many of the first metallurgists in this and other countries;[3] but the practical application of basic linings in the Bessemer converter is the outcome of Dr. Percy's teaching; for Mr. S. G. Thomas was a student of the School of Mines, and his partner, Mr. Gilchrist, is an Associate. Mr. Snelus is also an Associate, and Mr. Riley long worked in the metallurgical laboratory. The process not only gives hope that it will be possible to utilise the large quantities of ore in the well-known Cleveland district, but is also widely practised with success on the Continent.[4] It is probable, therefore, that the large deposits of ore in the basin of the Saar, and those of Lorraine and Luxembourg, which in extent are equal to the Cleveland district, while containing a much greater amount of phosphorus, will now be available. During a recent visit to the Hoerde Works in Westphalia, where I witnessed the operation, Herr Massenez, the director, told me that 10,000 tons of "Thomas-Gilchrist" metal have already been produced there since the adoption of the process a few months ago.

The metallurgy of copper presents several features of peculiar interest. Mr. Thomas Gibb (a student of my own year), whose work in connection with the extraction of copper by wet methods has been most important, reminds me that in 1863 the wet processes for extracting copper were insignificant; now over 40,000 tons of copper are annually produced by

[1] *The Times*, Dec. 31, 1879. [2] Metallurgy—Iron and Steel (1864), p. 819.
[3] M. Gruner, *Annales des Mines* (1869), t. xvi., p. 199.
[4] M. Gruner, *Annales des Mines*, pt. 1 (1879), p. 146. H. von Tunner, *Zeitschrift der berg- und hüttenmännischen Vereins für Steyermark u. Kärnten*, xii., Jahrg., Mai-Juni, 1880. Herr J. Massenez, *Engineering*, vol. xxx. (1880), p. 198.

their aid; much has also been learnt as regards other branches of its metallurgy.

In the case of lead, improvements have been introduced in the mode of purification that have proved to be of considerable importance. But these, as well as the modifications in the treatment of other metals, will require to be considered in some detail in the course of my lectures, and I would only now allude to the growth of the platinum industry in recent years as affording a striking instance of the application of scientific methods to metallurgy. In 1851 the amount of platinum separated from its associated metals and employed in the arts was probably not more than one-tenth of that now extracted. We owe the development of the use of this metal mainly to the eminent metallurgists, Messrs. Johnson, Matthey & Co., a well-known member of which firm was a student in Dr. Percy's laboratory. They early adopted the classical method of Deville and Debray; and by its aid now supply about 80 per cent of the total amount of this metal annually employed in the world, in addition to other metals of the platinum group, which they alone have isolated in quantity.

I had intended to indicate the metallurgical work done by the more prominent men who have been associated with the School, but I found that it would not be possible, in the brief time at my disposal, to do justice to such as Bauerman, Dick, Hackney, Pearce, Riley, Willis, and others, whose labours have placed them so high in the ranks of English metallurgists. You will, however, as the Course proceeds, have opportunity of becoming familiar with their names.

In referring to the past teaching of the School, I must remind you of the importance of rigorous and minute inorganic analysis; and it is the more necessary that I should do so from the fact that the peculiar charm of organic research appears, as has been already pointed out by Prof. Abel,[1] to lead the younger chemists, to "under-estimate the value and importance, in reference to the advancement of science, of the labours of the plodding investigator of analysis." I am satisfied, however, that, if we bear the traditions of the chemical and metallurgical laboratories of the School of Mines in view, we are not likely to underrate the importance of analytical work; and much conclusive evidence as to the value of the teaching of the past thirty years is afforded by the labours of the accomplished analysts who have, from time to time, worked under Dr. Percy's direction.

The direct influence of the School on the success with which metallurgy has been practised in this country has been most marked, and would alone afford an answer to the question whether the possession of high scientific attainments is generally advantageous to the successful conduct of metallurgical works. It must not be forgotten that our subject is constantly receiving valuable aid from branches of science other than chemistry; and this can hardly be better shown than by the growing importance of physical research in connection with metallurgical problems. I would incidentally remind you that it is the more important for us to consider this, because special attention was directed to the question in the evidence given before the Royal Commission on Scientific Instruction,[2] whose recommendations will, it is to be hoped, extend the influence of the School of Mines.

[1] *Brit. Assoc. Report*, Plymouth (1877), p. 44.
[2] Report, vol. ii., Minutes of Evidence, p. 86 (1874).

In connection with this branch of our subject a most prominent position must be given to the production of high temperatures, as it will be obvious that we have principally to consider the reactions of the elements when under the influence of heat. In the first half of the present century temperatures higher than the melting-point of zinc were not known with any degree of certainty; but in 1856 [1] M. Henri Ste. Claire-Deville pointed out that chemistry at high temperatures—that is to say, up to the blue-white heat at which platinum volatilises and silica fuses—remained to be studied. Since then, in conjunction with M. Troost, he has given us certain fixed points, such, for instance, as the boiling-points of cadmium and zinc; and Deville's researches on dissociation have entirely modified the views generally entertained in regard to the theory of combustion. Indeed, we owe so much to this illustrious teacher, that the best homage we can offer him will be to work in the directions he has indicated. M. Stas has proved that it is perfectly easy to distil even large quantities of silver from one lime crucible to another,[2] a fact which has been taken advantage of by Mr. Lockyer and myself in some experiments on the absorption-spectra of the vapours of certain metals at high temperatures.[3]

As regards scientific advance of a more essentially practical character, the gradual discovery of the fact that in certain cases fuel can be best employed if it be previously converted into gas, and the recognition of the advantages to be derived from a preliminary heating of the gases and the air, has led to the wide adoption of the regenerative system, by which the waste heat of the furnace is utilised for heating the incoming air or combustible mixture of air and gas necessary to effect the required operation. Dr. Siemens has thus shown us how to economise fuel to a vast extent, it being now possible to produce a ton of steel by the use of 12 cwts. of small coal instead of 3 tons of coke required to melt it in the old form of furnace. By the command of high temperatures, moreover, he has developed new processes in the metallurgy of iron, which are resulting in the replacement of the old "cinder-mixed" wrought iron by "cinder-free" ingot iron and steel.[4] The degree of heat attainable by the regenerative furnace is, however, limited to the temperature of dissociation of carbonic acid and aqueous vapour, so that the temperature never exceeds about 2,600° C.; but during the present year [5] Dr. Siemens has employed the far greater heat of the electric arc for the fusion of steel and platinum.[6] Bearing in mind the interest excited by recent experiments on the effect of intense heat on bodies now considered to be elementary, we may expect physicists to look to us for aid in developing the methods of employing high temperatures.

We shall have to consider very carefully the physical work which groups around the metallic alloys. It has long been known that the union of two

[1] *Ann. Chim. et Phys.* (3), t. xlvi., p. 182; *Comptes Rendus*, t. xc. (1880), p. 773.

[2] Sur les lois des proportions chimiques (1865), p. 37.

[3] *Proc. Roy. Soc.*, vol. xxiii. (1875), p. 344.

[4] Åkerman, *Journ. of the Iron and Steel Inst.*, 1878, No. 2, p. 360.

[5] *Engineering*, vol. xxix. (1880), p. 478.

[6] Figures convey but little impression as to such high temperatures; but it may be mentioned that Dewar has given 7,000° C. as approximately the temperature of the electric arc (*Brit. Assoc. Rep.*, 1873, p. 466), and, according to Rosetti, the true temperature of the sun can hardly be less than 10,000° C. or more than 20,000° C. *Phil. Mag.* (5), vol. viii., p. 550 (1879).

or more metals produces a result which often differs more in physical properties from either of its constituents than they do from each other. There is strong evidence that metals combine in chemical proportions; and we may turn with advantage to the class of alloys, certain of which have been in use from prehistoric times—the alloys of copper and tin. Here are two copper-tin alloys, one containing 61·7 per cent. of copper and the other 68·2 per cent. They correspond respectively to the formulæ $SnCu_3$ and $SnCu_4$; they only differ by 6·5 per cent., and yet their physical properties are in certain important respects totally distinct. This essential difference in their properties produced by a small difference of composition brings me to one very distinctive feature of metallurgy, the enormous influence exerted on a large mass of metal by a trace of another metal or metalloid—that is, by a quantity so small that it appears to be out of all proportion to the mass in which it is distributed.

I think it may safely be asserted, that in no other branch of applied science has the operator to deal with quantities that are at once so vast and so minute; and the Course will not have proceeded far before you will recognise this fact.

It may be that the trace to be extracted is alone of value—as, for instance, the few grains of gold that can be profitably extracted from each ton of a material, which, although containing only one part of gold in five millions by volume, is thereby entitled to be regarded as an auriferous deposit that can be profitably worked; or it may be the minute percentage of a metalloid which must be extracted, in order that the physical properties of a large mass of metal may not be entirely altered.

Let me give you a few instances of the influence of small traces of metal.

The presence of only $\frac{1}{300}$ per cent. of antimony in a mass of molten lead, the surface of which is exposed to the air, will cause it to be rapidly oxidised, while a similar mass of lead of equal surface, but free from the minute quantity of antimony, will be but slowly acted upon; and it has been shown by the late Mr. Baker, of Sheffield, a distinguished student of the School, that $\frac{7}{1000}$ per cent. of copper is detrimental to the lead employed in the manufacture of white lead.

The presence of $\frac{1}{20}$ per cent. of lead or certain other metals in standard gold will render a bar an inch thick so brittle that it may readily be broken by a slight rap with a hammer. Less than $\frac{1}{2}$ per cent. of iron in metallic copper will reduce the electrical conductivity by about 60 per cent., while a far smaller quantity will render it quite unfit for manufacture into telegraph cables, or for other electrical purposes.

In 1866, Graham showed,[1] by experiments with which I had the privilege of being connected, that the presence of occluded gases in metals often exerts a marked influence on their molecular structure. In the case of iron he urged that metallurgists should study the effects of occluded gases, more especially carbonic oxide, the weight of which, according to his experiments, could not exceed the $\frac{1}{15}$ per cent. of the weight of iron in which it was present. The significance of such facts is now under consideration by a Committee of the Institution of Mechanical Engineers;[2] and the question of the presence

[1] *Phil. Trans.*, 1866, p. 438.

[2] First Report of the Committee on the Hardening, Tempering, and Annealing of Steel, 1879.

of gas in steel, either occluded or retained in the form of bubbles, is further being investigated by Chernoff,[1] Muller,[2] and others.

There are many cases in which the malleability of metals is seriously compromised by the presence of oxygen, either dissolved or in a combined form. The addition, however, of a minute quantity of a metal or metalloid capable of combining with the oxygen without itself exerting an injurious influence on the metal produces a most marked beneficial effect. Thus, if $\frac{7}{100}$ per cent. of phosphorus in the form of phosphide of copper be added during the operation of "poling" copper, its action is stated to be most serviceable, although only $\frac{3}{100}$ per cent. is actually retained by the metal.[3]

It is, however, in the metallurgy of iron and steel that the influence of minute traces of impurity is most marked; and on this subject it will be necessary to enter into considerable detail during the course of lectures; but I must now confine myself to a few instances only. I have already referred to the importance of the elimination of phosphorus in the manufacture of malleable iron and steel. It is known that a minute quantity of this elementary body may be highly injurious to the metal, even if the relation between the carbon and manganese is favourable. I would refer, for instance, to the tests made on certain plates of Swedish puddled iron exhibited in the Paris Exhibition of 1878, which were found to have a far higher resistance to fracture by impact than certain other plates compared with them; and yet analysis proved that the main difference between them lay in the fact that the good plates contained only $\frac{2}{100}$ per cent. of phosphorus, whereas the inferior plates contained $\frac{1}{10}$ per cent. more.[4]

Carbon, it is well known, gives to iron fusibility, and renders it capable of being cast in moulds. The results of very many experiments appear to show that the presence of $\frac{15}{100}$ per cent. of carbon converts iron into steel, rendering it capable of being slightly hardened; beyond $1\frac{1}{2}$ per cent. of carbon the metal ceases to be malleable, and it is known as cast iron.

The influence of carbon on the tensile strength of steel is very remarkable. Mr. Willis, the able chemist of the Landore Siemens Steel Works, tells me that two samples under identically favourable conditions as to their content of sulphur and phosphorus, but containing $\frac{15}{100}$ and $\frac{18}{100}$ per cent. of carbon respectively, will differ by 6 tons per square inch in breaking-strain, or by an increase in the latter case of 27 per cent. But carbon is far from being the only metalloid that exerts a marked influence on the physical properties of iron. Manganese, for instance, is generally considered to act in a manner similar to carbon; and Willis has shown[5] that an ingot of a certain variety of steel containing no manganese will break into pieces at the first blow of the hammer, whereas a similar ingot containing $\frac{8}{100}$ per cent. of that metal will forge readily. The influence of phosphorus has already been referred to; and during the Course we shall consider together the manner in which the character of iron or steel is modified by the presence of minute quantities

[1] On the Structure of Cast-steel Ingots. Translated for the Institution of Mechanical Engineers by W. Anderson, C.E. (1879).

[2] Bericht der deutschen chemischen Gesellschaft, 1879, No. xii., 93. Glaser's *Annalen für Gewerbe und Bauwesen*, August, 1880, p. 138.

[3] W. Weston, *Phil. Mag.* (4), l., p. 542.

[4] Åkerman, *Journ. of the Iron and Steel Inst.*, 1878, No. 2, p. 363.

[5] *Journ. of the Iron and Steel Inst.*, 1880, No. 1, p. 92.

of sulphur, silicon, and other metalloids, as well as of a few metals. The problems to which they individually give rise are very complicated; but when several are present together the question becomes so involved that it will be long before we can hope for a complete solution.

Dr. Fleitmann, of Iserlohn, has recently shown [1] that nickel, which breaks under the rolls, may be made perfectly malleable by the addition of a little over $\frac{1}{10}$ per cent. of magnesium; and at the Düsseldorf Exhibition I saw thin sheets of large dimensions produced by his method. M. J. Garnier has also shown [2] that malleability may be ensured by adding $\frac{3}{10}$ per cent. of phosphorus.

A fact of much interest in relation to the assay of gold has been discovered by Dr. A. D. van Riemsdijk, of Utrecht,[3] who has shown that the presence of $\frac{1}{100}$ per cent. of certain metals of the platinum group may be detected by the fact that the cooling mass of molten metal does not "flash" or pass through the remarkable state known as "superfusion."

I must not further multiply instances, but will only mention that M. Nyst, of the Brussels Mint, has lately found that the presence of $\frac{15}{100}$ per cent. of silicon in standard gold will so affect its molecular grouping as to render it possible for a thin strip to bend by its own weight, as zinc would, in the flame of a candle.

The growing importance of physical research in connection with metallurgy is shown by the fact that physical methods are now constantly appealed to by those interested in metallurgy, more especially in the case of iron and steel. We are told, for instance, that the hardness of steel may be correctly inferred from a numerical determination of its coercive force; [4] it is sought to establish the actual nature of the change in the mode of existence of the carbon in steel that accompanies hardening by determining its thermo-electric properties; [5] and the hope is held out [6] to us that the time will soon come when boilermakers will electrically test their plates, possibly by the aid of the induction-balance, just as they now test them for ductility and tenacity. I can only add the expression of a belief that this powerful weapon of molecular research which Prof. Hughes has given us will yield good results in the hands of some of you.

The varied materials now used in the Bessemer and Siemens-Martin processes have greatly complicated what is known as ingot-metal; and the enormous increase in recent years in the use of certain varieties of steel has rendered it necessary to scrutinise more rigorously the analytical and other methods of estimating the amount of such elements as manganese, chromium, and silicon, the presence of which we have seen produces such remarkable effects. Many skilful observers have, therefore, as might have been expected, sought the aid of the spectroscope.

Its use for determining the point at which decarburisation has ceased

[1] *Deut. chem. Gesel.* (1879), vol. xii., p. 454. English Patent Specification, No. 5,126 (1878).

[2] *Comptes Rendus*, xci. (1880), p. 331.

[3] *Chemical News*, vol. xli. (1880), p. 126; *Ann. Chem. et Phys.* (5), tom. xx., p. 66.

[4] Trève and Durassier, *Comp. Rend.*, t. lxxx. (1875), p. 799. Wattenhofen, *Journ. of the Iron and Steel Inst.*, 1879, No. 1, p. 305.

[5] Barus, *Phil. Mag.* (5), vol. viii., p. 341.

[6] W. H. Johnson, *Chemical News*, vol. xlii. (1880), p. 70.

in the Bessemer converter was pointed out by Dr. Roscoe,[1] followed by Lielegg, Wedding, and Marshall Watts;[2] and more recently Messrs. Parry and Tucker,[3] of the Ebbw Vale Works, have shown that the influence of mere traces of certain impurities on the working of iron renders it very desirable to add spectroscopic observations to the ordinary chemical analysis. In 1874, Mr. Lockyer and myself made experiments on the quantitative analysis of certain alloys by means of the spectroscope;[4] and in the following year Sir John Alleyne[5] described a method for estimating small quantities of phosphorus in iron and steel by its aid, which possesses much interest.

The results of mechanical tests are even more important. Not long since the appearance of the fracture of a sample of metal was considered to afford trustworthy and sufficient evidence as to its nature and properties; but such rough methods have given place, in the hands of Kirkaldy and others, to the rigorous physical and mechanical investigation to which metals must now be submitted as a matter of ordinary routine. The results, tabulated or plotted into curves, which mark the influence of each constituent or impurity, form permanent records of the greatest value.[6]

The most careful mechanical and physical tests do not, however, necessarily supply all the information required. The complex varieties of iron and steel now used seem, as M. Lan has pointed out,[7] to be specially liable to what may almost be called a molecular mobility, in virtue of which, when subjected to shocks or vibrations of sufficient intensity, a structural re-arrangement is set up; of their behaviour under these circumstances the previous static tests by traction can give no indication.

It has only been possible for me to indicate the more important conditions affecting the successful practice of metallurgy. I have traced the relation between technical and scientific workers; but there is yet another condition of somewhat recent growth. The enormous scale on which operations are now conducted renders it more necessary than formerly for those engaged in metallurgical enterprise to seek the aid of capitalists. The result is that a large share in the control of many important works falls to the non-scientific members of the Board of Directors, men of high commercial ability, but whose knowledge of the importance of scientific work is necessarily limited. It is true that they may recognise the necessity for scientific aid in the works with which they are connected, but they are too often unconscious of the labour and difficulty that are involved in the attainment of accurate scientific knowledge. I am convinced, however, that facts are gradually compelling them to recognise that the value of a metal may entirely depend on whether it does or does not contain a trace of impurity, and that the exact method of treatment to be adopted depends much on the character of the materials employed; they will, therefore, examine more carefully than they have

[1] *Proc. Lit. and Phil. Soc., Manchester*, 1863, iii., p. 57.
[2] *Phil. Mag.* (4), vol. xxxiv., p. 437.
[3] *Journ. of the Iron and Steel Inst.*, 1880, No. 1, p. 163.
[4] *Phil. Trans.*, clxiv. (1874), p. 495.
[5] *Journ. of the Iron and Steel Inst.*, 1875, No. 1, p. 62.
[6] V. Deshayes, "Classement et Emploi des Aciers" (Paris, 1880); also *Bull. Chem. Soc.*, tom. xxxi. (1879), p. 166. H. Lebasteur, "Les Métaux à l'Exposition de 1878" (Paris, 1878).
[7] M. Lan, "La Métallurgie à l'Exposition de 1878" (Paris, 1879); also *Ann. des Mines*, Mai-Juin, 1879.

hitherto done the qualifications of men to whom important duties are entrusted, and will insist that the services of only adequately trained metallurgists shall be secured.

I shall have to direct your attention to the minute care with which details affecting commercial interests are now investigated; and your success will further depend on the facility with which you are able to use the "tools of thought" furnished by chemistry, physics, and mechanics. Whether you will ever possess the tact and judgment necessary to direct such works as Dowlais with an army of ten thousand people, obviously depends on personal qualifications which I can but little influence.

I venture to hope that you will, by original research, add to the general advance of science, for, as the late Prof. Clifford has reminded us, what have often proved to be the most useful parts of science have been investigated for the sake of truth and not for their usefulness.

Dr. Percy found metallurgy practised in this country mainly as an empirical art. He may well feel, to borrow the words of an old writer, that in his hands "the business of Metallurgy and Essaying has not only been illustrated, but also improv'd, amended and enrich'd"; for his works contain a record of its progress, his teaching and researches have secured it a scientific basis, and he has trained a body of scientific workers, in whose hands the immediate future of metallurgy to a great extent rests. Bearing in mind how much the progress of our science means to England, I cannot but be conscious that, in attempting to continue this work, I undertake a grave responsibility.

4th October, 1880.

The following letter was the last communication of Roberts-Austen to his students:—

ROYAL MINT,
November 8th, 1902.

TO THE STUDENTS OF THE METALLURGY CLASS,
ROYAL SCHOOL OF MINES.

After twenty-two years of work in the Royal School of Mines, my doctors absolutely forbid my lecturing for the present. My place, I am glad to say, will for a time be taken by my old friend, Mr. Gowland, himself a School of Mines man, who is well known to you already, and is a Metallurgist of wide reputation. I am sure that you will accord him the same patient attention you have given me, attention for which I am the more grateful as I am fully conscious that, owing to illness, my lectures have been delivered with great difficulty.

I need not remind you that my life-long interest in our School is undiminished, and I beg that you will remember that I shall be only too glad to see, at the Mint, any of you to whom my advice may be useful, for, believe me, the welfare of my men has my warmest solicitude.

Faithfully yours,

W. C. ROBERTS-AUSTEN.

ON THE DEVELOPMENT OF TECHNICAL INSTRUCTION IN METALLURGY.

An Address delivered by Roberts-Austen at the opening of the New School of Metallurgy in the Birmingham and Midland Institute, on the 24th of September, 1885.

The opening of the newly organised Class of Metallurgy in this well-known Institute is another important step in the technical teaching of the country, and I have accepted the invitation of the Council to deliver a brief address on this occasion with much pleasure, for more than one reason. I recognise in the efforts your Council are making to foster technical instruction in this special subject the realisation of views I have long held; and, further, the lecturer, Mr. Hiorns, by whom the metallurgical instruction here has now been conducted for some years, is my friend, and was a student of my own at the Royal School of Mines. I am anxious, therefore, to wish him success on entering on a more extended sphere of usefulness. In a circular which has been addressed to the manufacturers of Birmingham your Council has stated its conviction that:—

"A more complete course of metallurgy than has hitherto been possible here cannot fail to exert a great influence on the trades of the town and district, and it is hoped that by making workmen better acquainted with the scientific principles on which their trades are based, it will be possible to battle more successfully with our foreign competitors, who, in many respects, have the advantage of us in the superior scientific training they have received."

While we admit that this is true, it may be well to remember a caution given by an old writer, W. Carnwise, in 1583, who held that judgment was more to be commended in recognising the skill of certain foreign artificers and craftsmen than in ignoring the ability, or, as he called it, the "activity" of our people, "who," he says, "owte of all p'adventure be as skylfull in myning, as hard and dyligent laborers, and as good chepe workmen in that kind of travell as are to be found in Europe."

It is not a little strange that the systematic instruction in metallurgy in this country, to which the metal industries are all-important, should be of comparatively recent date. We appear to have imitated the system of the early metallurgists and alchemists (and for their work I can hardly claim too much respect), who handed down their traditions and discoveries through one or two pupils, for we find the master and disciple system surviving with singular vitality into recent times.

It is well known, especially in Birmingham, that metallurgy has progressed in two ways; first, by the technical skill of the craftsmen leading them a long way in advance of theory to the acquisition of important facts; and, second, by discoveries resulting from the application of purely scientific methods of procedure. The German miners and smelters introduced into this country by Queen Elizabeth were skilled craftsmen; but still the greatest advances in theoretical metallurgy were, even until quite recent times, the result of individual and not collective teaching. For just as in the thirteenth century Albertus Magnus had S. Thomas Aquinas for his pupil, both being metallurgists, so in the seventeenth century Becher, who lived in this country and smelted tin here, transmitted to his famous pupil Stahl the theory of

Phlogiston, which was mainly built up on a metallurgical basis, and the effect of which, both on scientific and technical progress, was so marked. Towards the end of the eighteenth century, what is now called technical education was pleaded for by an accurate metallurgical writer, Bishop Watson, Professor of Divinity at the University of Cambridge, who strongly insisted on the importance of the purely economic side of our subject, and who urged that the improvement in metallurgy and other mechanic arts dependent on chemistry would best be entrusted to an "Academy," the labours of which should be devoted to that particular purpose." In my opinion, from the time 1782, when this wise prelate wrote, to the foundation of the Royal School of Mines in 1851, there is no event affecting the systematic teaching of our subject of anything like equal importance to the appointment of Dr. Percy as the first holder of the Chair of Metallurgy there.

I have elsewhere[1] attempted to trace the development of the metallurgical work of the country to their origin in Dr. Percy's labours. The evidence of their value is clearer to me now than when I delivered my introductory lecture at the School of Mines five years since, and the sense of the importance of Dr. Percy's influence will, I trust, deepen as my own experience grows. We must, however, devote ourselves now chiefly to the progress that has been made quite recently. The results of the investigations of the Select Committee appointed in 1868 to enquire into the Provisions for giving Instruction in Theoretical and Applied Science to the Industrial Classes will be familiar to many of you, and the importance of the question in relation to metallurgy has been specially recognised by the Lords of the Committee of Council on Education, who, in 1882, took what was, from our point of view, the very important step of directing that metallurgy should be taught as far as might be possible, *practically* to the students who present themselves for the May examinations. I am glad to be able to claim that the school we open to-night was, under the guidance of your Council, mainly the outcome of the action of the Science and Art Department; which is now, I am satisfied, making full provision for the primary instruction in metallurgy of foremen and artificers throughout the country, a view which is well borne out by the results of the examinations I have recently conducted. Its direct influence on the higher teaching of metallurgy I will endeavour to trace later on.

The advantages of technical education which the pressure of necessity is now slowly forcing on the country are so generally appreciated in Birmingham, that I need only dwell on the special claim of metallurgical teaching to the support of all who are interested in the great industries of the town. While it is unnecessary for me to justify the scientific teaching of the subject, it is perhaps more important than ever that the true relation of theory and practice should be clearly understood; and here considerations based upon the dual character of our work—that is, its practical and its scientific aspects—again present themselves. There are many metallurgical operations in conducting which the highest success can alone be secured by the subtle skill of sight or touch while the power to deal with new and unfamiliar conditions which education might impart to workmen would appear almost to diminish rather than increase the usefulness of those entrusted with certain definite operations. My earliest impressions on this point were gathered in Birmingham, the principal works of which I visited sixteen years ago, together

[1] See pp. 84-98.

with the late M. H. de Jacobi, of St. Petersburg, whose name will be familiar to you, as he was one of the earliest workers in the field of electro-metallurgy; and I then learned how many men there are carrying on routine work with wonderful exactness, yet their only school was the workshop, and not the lecture-room or laboratory. It may, however, be urged that even such practical men of the high order of merit I am contemplating, should at least know certain scientific facts by which their practice may be supported; and no less an authority than Jules Simon, formerly Minister of Public Instruction in France, has said, "The practised eye and the sure hand are worth much, but they do not replace science. The smith, who knows the disadvantages of too rapid oxidation, who understands why throwing water on the surface of ignited fuel increases the heat of the centre of the mass; the puddler who takes into account the effects of a reducing flame, and who employs it or an oxidising flame at will; such men are evidently the most important workmen, more skilful for current needs, less disconcerted by an accident, less embarrassed by having to describe an operation, less slaves to routine, quicker to adopt a new process." He adds, "but without speaking of the daily details of work, of accidents guarded against, or of remedies improvised, is it nothing, that by training workmen properly an impulse is given to the genius of discovery? . . . It is sometimes necessary to separate practice and theory because life is short, but they should always be combined when possible because life is complex. It is necessary to join practice with theory, as in another order of ideas it is necessary to unite capital and labour, because one only sees a problem thoroughly by looking at both sides of it." The more intelligent the workman becomes the more he will appreciate the ability of those who direct him. He will, as the result of education, take keener interest in his work, and his social position will be materially improved, even though his daily wage is not augmented.

I cannot trace to-night the methods that are adopted on the Continent to ensure the efficient training of artificers and foremen; the literature of technical instruction is now abundant enough, and I must refer you to the various reports which have from time to time been published; but permit me to say that in the laboratories you will presently visit and in the appliances and arrangements which have been provided by the Council, you have an admirable equipment, and in my opinion the Midland Institute is in a position to carry out with high efficiency the kind of instruction which is contemplated. The question now naturally presents itself, what evidence or probability is there that the education to be provided will be advantageous in the sense that it will "pay," which, of course, is the object of all improvement in conducting metallurgical operations. I do not want to multiply references to authority, but let me once more appeal to the Bishop, Dr. Watson, to whom I have referred to as being one of the first to plead for systematic technical instruction. He said, a century since, "there is a certain standard of perfection in the exercise of every art which is not always well understood, . . . and he who should apply himself to the solution of the problem (the extraction of the greatest possible quantity of metal from any particular kind of ore) . . . must take into consideration another circumstance of as much importance as the quantity of metal to be extracted—the expense attending the operation."

In estimating the advantage of special technical instruction in metallurgy, it is necessary to bear in mind the two characteristic features of the art of extracting metals from their ores and fitting them for industrial use. First, the history of metallurgy abounds with instances showing that an apparently trifling improvement in an operation, or, it may be, in the composition of an alloy, has been followed by large pecuniary gain, the amount of which would seem to be out of all proportion to the scientific merit of the discovery which led to the change. A suggestion gathered in the laboratory may prove a source of wealth when developed in the works, and it will be the special duty of the teachers who will so soon attack the comprehensive syllabus of the practical classes to indicate the direction in which improvements may be made, and to suggest the nature of the changes to be introduced into practice.

The second prominent feature of metallurgy to which I would allude is the enormous influence exerted on a large mass of metal by a trace of another metal or metalloid; that is, by a quantity so small that it appears to be out of all proportion to the mass in which it is distributed. I might adduce instance after instance in support of this point, but it is unnecessary to do so. Workers in the precious metals in Birmingham well know how small a trace of impurity will render gold alloys brittle; and, conversely, it is equally well known that the addition of a very small amount of certain metals to nickel will convert a very brittle mass into a perfectly malleable and ductile one. Electro-platers are familiar with the consequences which may result from a slight change in the composition of a depositing-bath. Or, to turn to less familiar points, I think you would be surprised if it were possible to show you some experiments I have recently made on the effect on the tenacity of certain alloys when the surface tension of wires, into which the alloys were drawn, is released by touching the wires with a mild pickling solution. Consider, again, what a large portion of the vast field presented by metallic alloys remains entirely unexplored, and how substantial the rewards of discovery in this direction are. In Birmingham what may be called the mechanical side of metallurgy is specially important, as the industries of this town are so largely devoted to working metals, and not to extracting them from their ores. The laboratories here are specially arranged in view of this fact.

It will be of the utmost importance to show the way in which preventible waste in conducting mechanical operations on metals may be reduced to the narrowest possible limits, by vigilant individual efforts, and to point to the advantage a careful workman has over one who is less attentive, though not less skilful.

It will be interesting to watch the effect of the establishment of this and other classes in the industrial centres, in enabling the higher instruction in metallurgy to be developed; and as Birmingham will, I trust, continue to furnish many Exhibitioners to the Royal School of Mines at South Kensington and Jermyn Street, it may be well for me to endeavour to indicate what is, and should be, the nature of the instruction offered in Schools of Mines generally.

To take first our own School of Mines, which for more than thirty years has provided technical instruction in metallurgy and mining. Since its establishment in 1851 it has trusted to elaborate lectures, and has devoted

special care to a complete system of laboratory work. The Ecole des Mines, in Paris, adopts a system which is in the main the same, but the students visit and report upon works during their vacation—a plan I have endeavoured to imitate since my appointment to the Chair at the School of Mines in 1880. Second, there is what may be called the System of Freiberg, as it is so well represented at the great school in Saxony, where the men study metallurgy theoretically, in lectures to which a somewhat limited laboratory course is added, the great feature of the instruction being the facilities the men have for spending a portion of each day in the Halsbrücke Hütte or the Muldener Hütte, these being the great works of the district in which the school is situated. And, finally, there is the system adopted in America, especially at the School of Mines, Columbia College, New York, and at the Massachusetts Institute of Technology at Boston, where, in addition to laboratory work as ordinarily understood, students carry out metallurgical operations, more or less experimentally it is true, but, as an engineer would say, on a scale of nearly "12 inches to a foot."

It is somewhat difficult to compare the relative merits of these apparently distinct systems, because the conditions of the countries in which they are in force are so different. In London, Paris, New York, and Boston the Mining Schools are situated at some distance from metallurgical centres. From an American point of view the distance of London from S. Wales, Lancashire, and Yorkshire must seem insignificant; but distance is not the only difficulty to be met. In this country the works are not under Government control, and students, therefore, owe their admission to works to the generosity of the owners, which has hitherto been so liberally exercised in the case of my own students that the absence of State influence has not been felt. On the Continent the control of works by the Government enables students to visit the various establishments as a matter of right, and this fact has doubtless determined the situation of certain Mining Schools. Although no strict comparison can be made, the following appear to me to be the prominent points connected with the three systems. Our own school was established at a time when, as we have seen, the systematic teaching of metallurgy in this country had been neglected. It was only natural, therefore, that extreme importance should be attached to laboratory work, and especially to researches having for their object the investigation of obscure points in metallurgical practice. There is, in fact, far too great a tendency at the present day to lose sight of the importance, from an educational point of view, of basing the teaching of students on a thorough knowledge of the chemical reactions upon which metallurgical operations must depend, and on vigorous and minute chemical analysis. I can only repeat an earnest appeal of Sir F. Abel[1] to the younger chemists, not to under-estimate the value and importance, in reference to the advancement of Science, of the labours of the plodding investigator of analysis.

The wealth of results obtained by the investigations conducted by my distinguished master and predecessor, and above all by the success in all quarters of the world of our School of Mines men, affords an abundant justification of the plan which has hitherto been adopted: we have at least trained a body of accurate observers ready at all times to bring scientific reasoning to bear upon new sets of conditions.

[1] *Brit. Assoc. Report*, Plymouth (1877), p. 44.

With regard to the Freiberg system, its chief merit appears to me to consist in giving the student broad views as to practical details, if it does not familiarise them with the real difficulties of metallurgical work. I am always glad to receive students in my own class who come from metallurgical centres, but, on the other hand, in my opinion it is very easy to over-rate the advantage to be derived from placing the advanced students in the midst of works. No doubt a metallurgical atmosphere pervades the works, and there is much in the spirit of the student's surroundings, but the number of metals treated in any one district must necessarily be limited, while many processes of vast importance are wholly unrepresented. Surely, it may be urged, the frequent opportunities for seeing metallurgical operations must be of great benefit to the student; but consider how short a time a student, who is preparing for the higher branches of his profession, can possibly give to the purely theoretical work which he must get through. Such a student has no leisure in addition to that which should be set aside for exercise; and if he had leisure, I do not think he would be putting it to the best advantage if he were to devote it to looking on at a metallurgical operation conducted by someone else; and I believe that no system by which a student accompanies a demonstrator, or even a local foreman, to works, and only sees the successes and not the failures of other people's labours, really affords him adequate instruction.

I agree entirely with the remarks of my friend Prof. R. H. Richards, of Boston, upon this point. He observes "that large works cannot afford to spoil a furnace charge to show a student what happens from a little carelessness. A well-regulated establishment may go on for a long time without such a slip, and unless the superintendent is used to giving instruction, or takes pleasure in it, a student may be months at a works without finding out what the key to the success of the establishment is." [1]

In the American Schools of Mines plant of sufficient power is provided to render it possible to concentrate by the ordinary dressing appliances no less than 4 tons of any given ore, and to treat the enriched product by a suitable metallurgical process, adopting either "dry" or "wet" methods, or both combined, as the necessities of the case demand; and it may be added that the "plant" provided is sufficiently comprehensive to permit the adoption of very varied methods of treatment.

The foregoing is a brief sketch of the plan which is being gradually introduced into the Royal School of Mines. During the past session one student studied the extraction of gold from pyrites as practised at Grass Valley, California, and another extracted silver from its ore by pan amalgamation. Even in the metallurgy of iron much may be done by small appliances, and I am specially grateful to Mr. P. C. Gilchrist for having given to the School of Mines the small blowing engine and accumulator used by himself and the late Mr. Sydney G. Thomas in their well-known researches which led to the development of the basic Bessemer process.

The experience I have already gained of this method of instruction has satisfied me that by actually conducting experiments on a large scale students realise more fully than in any other way the absolute dependency of metallurgy upon chemistry. The value of assaying, in controlling the results

[1] Paper read at the Wilkes-Barre meeting of the American Institute of Mining Engineers (1870).

of their work, becomes evident, and the men learn, as Prof. Richards observes, "by their own experience that little losses taking place here and there and everywhere in their work mount up enormously in their final account of stock, and they are led to understand that failures in mines and works quite as often result from errors in judgment as they do from poverty of the deposits or defects in the processes adopted."

It will, I trust, have been understood that I have been speaking only of the training of a student; his career as a metallurgist can only be perfected in the works, because the manager has not only to deal with metals but with men.

We need never fear that by any amount of technical education we shall, by moulding men to the ideas of any particular school, set limits to the efforts of genius: the unexpected will happen in metallurgy in the future as in the past. Individual character will always assert itself, and the necessity for individual exertion will be as great as ever. We may help intelligence to do what it can; genius will do what it must.

Increased efficiency in the instruction in the industrial centres will directly influence, and will be reflected in, the teaching of the Royal School of Mines, so that, if only "for my brethren and companions' sakes, I will wish thee prosperity."

THE RELATION BETWEEN THEORY AND PRACTICE IN METALLURGY.

PRESIDENTIAL ADDRESS TO THE CHEMICAL SECTION OF THE BRITISH ASSOCIATION, CARDIFF, 1891.

The selection of Cardiff as a place of meeting of the British Association led to the presidency of Section B being entrusted to a metallurgist. It will be well, therefore, to deal in this address mainly with considerations connected with the subject to which my life has been devoted, and I hope that it may be possible for me to show that this practical art has both promoted the advancement of science and has received splendid gifts in return.

It is an art for which in this country we have traditional love; nevertheless the modes of teaching it, and its influence on science, are but imperfectly understood and appreciated. Practical metallurgists are far too apt to think that improvements in their processes are mainly the result of their own experience and observation, unaided by pure science. On the other hand, those who teach metallurgy often forget that for the present they have not only to give instruction in the method of conducting technical operations, but have truly to educate, by teaching the chemistry of high temperatures at which ordinary reactions are modified or even reversed, while they have further to deal with many phenomena of much importance, which cannot, as yet, be traced to the action of elements in fixed atomic proportions, or in which the direct influence of the atom is only beginning to be recognised.

The development of a particular art, like that of an organism, proceeds from its internal activity; it is work which promotes its growth and not the external influence of the environment. In the early stage of the development of an industry the craftsmen gather a store of facts which afford a basis for the labours of the investigator, who penetrates the circle of the "mystery" and renders knowledge scientific. Browning, inspired by the labours of a chemist, finely tells us in his "Paracelsus":-

> "To know
> Rather consists in opening out a way
> Whence the imprisoned splendour may escape,
> Than in effecting entry for a light
> Supposed to be without."

If it be asked who did most in gaining the industrial treasure and in revealing the light of chemical knowledge, the answer is certainly the metallurgists, whose labours in this respect differ materially from others which have ministered to the welfare of mankind. First, it may be urged that in no other art have the relations between theory and practice been so close and enduring. Bacon, who never undervalued research, tells us that in the division of the labour of investigation in the New Atlantis there are some "that raise the former discoveries by experiment into greater observations, axioms, and aphorisms: these we call the *interpreters of nature.*" There are also others "that bend themselves, looking into the experiments of their fellows and casting about how to draw out of them things of use and practice for man's life and knowledge . . . these we call the *dowry men or benefactors.*" In reviewing the history of metallurgy, especially in

our islands, it would seem that the two classes of workers, the interpreters of nature and the practical men, have for centuries sat in joint committee, and, by bringing theoretical speculation into close connection with hard industrial facts, have "carried us nearer the essence of truth."

The main theme of this address will, therefore, be the relation between theory and practice in metallurgy with special reference to the indebtedness of the practical man to the scientific investigator.

We will then consider—

(1) Certain facts connected with "Oxidation" and "Reduction," upon which depend operations of special importance to the metallurgist.
(2) The influence in metallurgical practice of reactions which are either limited or reversible.
(3) The means by which progress in the metallurgic art may be effected, and the special need for studying the molecular constitution of metals and alloys.

(1) The present year is a memorable one for chemists, being the centenary of the birth of Faraday and the bi-centenary of the death of Robert Boyle. The work of the former has recently been lovingly and fittingly dealt with in the Royal Institution, where he laboured so long. I would, in turn, briefly recall the services of Boyle, not, however, on account of the coincidence of date, but because with him a new era in chemistry began. He knew too much about the marvellous action of "traces" of elements on masses of metal to feel justified in pronouncing absolutely against the possibilities of transmutation, but he did splendid service by sweeping away the firm belief that metals consist of sulphur, salt, and mercury, and by giving us the definition of an element. He recognised the preponderating influence of metallurgy in the early history of science, and quaintly tells us that "those addicted to chemistry have scarce any views but to the preparation of medicines or to the improvement of metals," a statement which was perfectly correct, for chemistry was built up on a therapeutic as well as a metallurgic basis. The fact is, however, that neither the preparation of materials to be employed in healing, nor the study of their action, had anything like the influence on the growth of theoretical chemistry which was exerted by a few simple metallurgical processes. Again, strange as it may seem, theoretical chemistry was more directly advanced by observations made in connection with methods of purifying the precious metals, and by the recognition of the quantitative significance of the results, than by the acquisition of facts incidentally gathered in the search for a transmuting agent. The belief that chemistry "grew out of alchemy" nevertheless prevails, and has found expression in this Section of the British Association. As a fact, however, the great metallurgists treated the search for a transmuting agent with contempt, and taught the necessity of investigation for its own sake. George Agricola, the most distinguished of the sixteenth-century metallurgists, in his work "De Ortu et Causis Subterraneorum" (lib. v.), written about the year 1539, disdainfully rejects both the view of the alchemists that metals consist of sulphur and mercury, and their pretended ability to change silver into gold by the addition of foreign matter.

Biringuccio (1540) says, "I am one of those who ignore the art of the alchemists entirely. They mock nature when they say that with their medicines they correct its defects, and render imperfect metals perfect." "The art," he adds, "was not worthy of the consideration of the wise ancients who strove to obtain possible things." In his time, reaction between elements meant their destruction and reconstitution, nevertheless his sentence "transmutation is impossible, because in order to transmute a body you must begin by destroying it altogether," suggests that he realised the great principle of the conservation of mass upon which the science of chemistry is based. We have also the testimony of the German metallurgist, Becher, who improved our tin-smelting in Cornwall. He is said to have caused a medal to be struck in 1675 which bore the legend: "Hanc unciam argenti finissimi ex plumbo arte alchymica transmutavi," though he should have been aware that he had only extracted the precious metal from the lead, and had not transmuted the base one. This is a lapse which must be forgiven him, for his *terra pinguis* was the basis of the theory of Phlogiston, which exerted so profound an influence for a century after his death, and he wrote, "I wist that I have got hold of my pitcher by the right handle, for the pseudo-chemists seek gold, but I have the true philosophy, science, which is more precious."

At this critical period what was Boyle doing when the theory of phlogiston dawned in the mind of the metallurgist Becher? In 1672, Boyle wrote his paper on "Fire and flame weighed in the balance," and came to the conclusion that the "ponderous parts of flame" could pass through glass to get at melted lead contained in a closed vessel. It has been considered strange that he did not interpret the experiment correctly, but he, like the phlogistic chemists, tried to show that the *subtilis ignis*, the material of fire or phlogiston, would penetrate all things, and could be gained or lost by them. Moreover, his later experiments showed him that glass was powerless to screen iron from the "effluvium of a loadstone." His experiment with lead heated in a closed glass vessel was a fundamental one, to which his mind would naturally revert if he could come back now and review the present state of our knowledge in the light of the investigations which have been made in the two centuries that have passed since his own work ceased. If he turned to the end of the first century after his death he would see that the failure to appreciate the work of predecessors was as prevalent in the eighteenth century as in the sixteenth. The spirit of intolerance which led Paracelus to publicly burn, in his inaugural lecture at Basle, the works of Galen, Hippocrates, and Avicenna, survived in the eighteenth century when Madame Lavoisier burnt the works of Stahl, but it was reserved for the nineteenth century to reverently gather the ashes, recognising that when the writers of the School of Becher spoke of phlogiston they meant what we understand by potential energy.

If Boyle, finding that the Fellows of the Royal Society had not carried out their intention to build a "Repository and Laboratory," sought the School of Mines and came to the Royal College of Science he would surely thank my colleague, Prof. Thorpe, for his vigorous defence last year, as President of this Section, of the originality of the work of Priestley and Cavendish, to which Boyle's own researches had directly led. We on our part, remembering Berzelius's view that "oxygen is the centre point round

which chemistry revolves," would hope to interest him most by selecting the experiments which arose out of the old metallurgical operation of separating the precious metals from lead by "cupellation." When, in conducting this operation, lead is heated in the presence of air it becomes converted into a very fluid dross. Boyle had, in 1661, taken this operation as the very first illustration in his "Sceptical Chymist" in proof of his argument as to the elemental nature of metals. He would remember the quantitative work of Geber in the eighth century, who stated that the lead so heated in air acquired a "new weight," and he would appreciate the constant reference to the operation of cupellation from the close of the sixth century B.C., when the prophet Jeremiah wrote, to the work of Jean Rey in 1629, whose conclusions he would wish he had examined more closely. Lord Brouncker, as first President of the Royal Society, had called attention to the increase in weight of the lead in the "coppels" in the Assay Office in the Mint in the Tower, and Mayo had shown that the increase in weight comes from a distinct "*spiritus*" in the air. Boyle would incidentally see that Newton had accepted office in the Mint, where he doubtless continued his experiments on calcination begun some time before, and, as if to mark his interest in the operation of assaying, figures are represented on a bas-relief on his tomb in Westminster Abbey as conducting cupellation in a muffle. The old work merges wonderfully into the new. Chevreul, in the nineteenth century, confirms Otto Tachen's view in the seventeenth, as to the saponifying action of litharge. Deville employs molten litharge to absorb oxygen dissociated from its compounds, and Graham, by extracting occluded gases from iron and other metals, proves the accuracy of the old belief that elastic fluids can freely permeate even solid metals.

We may imagine with what vivid interest Boyle would turn, not merely to the results of Priestley's work, but to his methods. Priestley had decomposed litharge with the electric spark, and had satisfied himself in 1774 by heating red lead that the gas he obtained in his earlier experiments was really the one now called oxygen.

Boyle would see that in the period 1774-7 Lavoisier, being attracted by the "sceptical chemist's" own experiment on the heating of lead in closed vessels, overthrew the phlogistic theory and placed chemistry on a firm basis by showing that the increase in weight of lead and tin, when heated in air, represents exactly the weight of the gaseous body added, and, finally, Dalton having developed the atomic theory and applied it to chemistry, Berzelius made lead memorable by selecting it for the first determination of an atomic weight.

Without diverting his attention from the phenomena of oxidation, Boyle would find questions the interest of which is only equalled by their present obscurity. He would contemplate the most interesting phase of the history of chemical science, described by van 't Hoff as that of its evolution from the descriptive to the rational period, in the early days of which the impossibility of separating physics and chemistry became evident, and Boyle would find that chemistry is now regarded from the point of view of the mechanics of the atoms.

Deville's experiments on dissociation have rendered it possible to extend to the groups of atoms in chemical systems the laws which govern the fusion and vaporisation of masses of matter, and this has produced a revolution

comparable in its importance to that which followed the discovery of the law of definite proportions, for dissociation has shown us that true causes of chemical change are variations of pressure and of temperature. For instance, oxygen may be prepared on an industrial scale from air by the intervention of oxide of barium heated to a constant temperature of 700°, provided air be admitted to the heated oxide of barium, under a pressure of 1½ atmospheres, while the oxygen, thus absorbed, is evolved if the containing vessel be rendered partially vacuous. It will be evident, therefore, that at a certain critical temperature and pressure the slightest variation of either will destroy the equilibrium of the system and induce chemical change.

The aim of Boyle's chemical writings was to show that no barrier exists between physics and chemistry, and to "serve the commonwealth of learning by begetting a good understanding betwixt the chemists and the mechanical philosophers," who had, as he said, "been too great strangers to each other's discoveries." In view of the dominant lines of research which occupy chemists at the present time, such, for instance, as the investigations of "osmotic pressure" and of the application of Boyle's own law to salts in solution, he would feel that his hope had been realised, and that, though he lived a century too soon to take part in Berthollet's discussion with Proust, he nevertheless shares Berthollet's triumph in the long-delayed but now rapid development of chemistry as a branch of applied mechanics.

We need, however, no longer look at these questions from the point of view of Boyle, for our own interest in the application of chemical mechanics to metallurgy is sufficiently vivid, as instances to be given subsequently will show.

Hitherto I have mainly dwelt on questions relating to oxidation, but not less interesting is the history of the steps by which an accurate knowledge was acquired of the other great process practised by the metallurgist, the one to which Paracelsus was the first to apply the name of "Reduction." Its explanation followed naturally from the elucidation of the phenomena of combustion by Lavoisier, who in continuation of Macquer's experiments of 1771 proved, in conjunction with other workers, that carbonic anhydride is produced when the diamond is burnt in air or oxygen. Carbon has been known for ages as the most important of the reducing agents, but when, in 1772, Lavoisier heated oxide of lead and carbon together, he did not at first recognise that carbonic anhydride had been produced, simply because the volume of the gas set free was the same as if oxygen merely had been liberated. He soon, however, saw that neither the carbon alone, nor the oxide of lead alone, gave rise to the evolution of carbonic anhydride, which resulted from the *mutual action* of carbon and a constituent of the litharge. "This last observation leads us insensibly," he adds, "to very important reflections on the use of carbon in the reduction of metals." It most certainly did, and by 1815 an accurate, if incomplete, view of reduction had passed into the encyclopædias. It was seen that the removal of oxygen from burnt metals, by carbon, "give the metals," as Fourcroy and Vauquelin put it, "a new existence." Some ten years later Le Play attempted to show that reduction is always effected by the intervention of carbonic oxide, which elicited the classical rejoinder from Gay-Lussac, who pointed out that "carbon alone, and at very moderate temperatures, will reduce certain metallic oxides

without the intervention of carbonic oxide or of any other elastic fluid." I mention these facts because metallurgists are slow to recognise their indebtedness to investigators, and too often ignore the extreme pains with which an accurate knowledge has been acquired of the principles upon which their processes have been based.

The importance of a coherent explanation of reduction in smelting pig-iron is enormous. The largest blast furnaces in 1815 hardly exceeded those in use in the previous century, and were at most only 40 feet high with a capacity of 5,000 cubic feet. At the present day their gigantic successors are sometimes 90 feet high with a capacity of 25,000 cubic feet. This development of the blast furnace is due to the researches of a number of investigators, among whom von Tunner, Lowthian Bell, and Grüner deserve special mention. We are, however, forcibly reminded of the present incompleteness of our knowledge of the mechanism of reduction, when we remember that the experiments of H. B. Baker have led us to believe that pure carbon cannot be burnt in perfectly dry and pure oxygen, and therefore that the reducing agent, carbonic oxide, would not be produced at all unless moisture be present.

Ludwig Mond, Langer, and Quincke teach us not only that nickel can separate carbon from carbonic oxide, but the wholly unexpected fact that dry carbonic oxide can at a temperature of 100° take up nickel, which it again deposits if heated to 150°. Mond and Quincke, and independently, Berthelot, have since proved the existence of the corresponding compound of iron and carbonic oxide, and it may safely be concluded that in the blast-furnace smelting of iron this peculiar action of carbonic oxide plays an important part, and it doubtless aids the carburisation of iron by cementation. It is truly remarkable that the past year should have brought us so great an increase in our knowledge of what takes place in the reduction of an oxide of iron, and in the carburisation of the liberated metal. My own experiments have, I trust, made it clear that iron can, at an elevated temperature, be carburised, by the diamond *in vacuo;* that is, in the absence of anything more than "a trace" of an elastic fluid or of any third element. Osmond has further shown within the last few months that the action between iron and carbon is a mutual one, for though carbon in the pure diamond form carburises iron, the metal in its turn, at a temperature of 1,050°, attacks the diamond, invests it with a black layer, and truly unites with it.

The question of the direct carburisation of iron (Darby's process) by filtering the molten metal through carbon, promises to be of much importance, for at present, as is well known, two millions of tons of steel which are made in the Bessemer converter in this country alone, are recarburised after "the blow" by the addition of spiegeleisen.

Carbonic oxide, moreover, would appear to be more chemically active than had been supposed; for during the present year Berthelot has shown that the perfectly pure gas heated to 500° or 550° produces carbonic anhydride with deposition of carbon at red heat, not by ordinary dissociation, but by decomposition preceded by polymerisation. He further shows that carbonic oxide will decompose ammoniacal nitrate of silver, and thus brings it into close connection with the aldehydes.

(2) In turning to the modern aspects of metallurgical practice, we shall see that the whole range of the metallurgist's field of study is changing. It

is no longer possible for him to devise a series of operations on the evidence afforded by a set of equations which indicate the completion of an operation; he has, as I have already suggested, to consider the complicated problems which have been introduced into chemistry from the sciences of physics and mechanics. He has, in fact, no longer to deal merely with atoms and molecules, but with the influence of mass. As Ostwald points out, we are reminded that many chemical processes are reciprocating so that the original bodies may be obtained from the product of the reaction. The result of such opposed processes is a state of CHEMICAL EQUILIBRIUM, in which both the original and the newly-formed substances are present in definite quantities that remain the same so long as the conditions, more especially temperature and pressure, do not undergo further change. Again, in very many metallurgical processes, reactions are rendered incomplete by the limitations imposed by the presence of bodies which cannot be speedily eliminated from the system, and the result may be to greatly retard the completion of an operation. The time has come when the principles of dynamic chemistry must be applied to the study of metallurgical problems if they are to be correctly understood, and it is, moreover, necessary to remember the part played by the surface separating the different aggregates in contact with one another. When, for instance, a reaction has to take place accompanied by the evolution of gas, there must be space into which gas can pass. The rate, therefore, at which change takes place will obviously depend on the state of division of the mass.

One of the most remarkable points in the whole range of chemistry is the action engendered between two elements capable of reacting by the presence of a third body. It may be, and this is the most wonderful fact of all, that merely a trace of a third body is necessary to induce reaction, or to profoundly modify the structure of a metal. H. Le Chatelier and Mouret have pointed out that in certain cases it is inaccurate to say that the third body causes the reaction to take place, because, after it has destroyed the inter-molecular resistances which prevented the reaction taking place, the third body ceases to intervene. This is apparently the case when platinum sponge effects the union of oxygen and hydrogen, or conversely, when very hot platinum splits up water vapour into its constituent gases. Future investigation will, it is to be hoped, show whether the platinum does not exert some direct action in both cases. We can no longer neglect the study of such questions from the point of view of their practical application. The manufacture of red-lead presents a case in point. In "drossing" molten lead, the oxidation of the lead is greatly promoted by the presence of a trace of antimony, and conversely, in the separation of silver from molten lead, by the aid of zinc, H. Roessler and Endelmann have recently shown that aluminium has a remarkable effect in protecting the zinc from loss by oxidation, and, further, the presence of one-thousandth part of aluminium in the zinc is sufficient to exert this protecting action on that metal. I am satisfied that if our metallurgists are to advance their industrial practice, they must, if I may use such an expression, persistently think in calories, and not merely employ the ordinary atomic "tools of thought." They will then be able to state what reactions can, under given conditions, take place; to indicate those which will be completed; and to avoid those that are impracticable.

In France, the country of so many great metallurgists, men like

Le Chatelier and Ditte are doing admirable service by bringing the results of the labours and teaching of St. Claire Deville within the range of practical men. And if I do not refer more specifically to their work it is for want of space and not of appreciation, but a few simple cases of reversible actions will perhaps make the subject clear. In the blast furnace the main reducing agent, carbonic oxide, is produced from the solid fuel by the reaction $CO_2 + C = 2CO$, a reaction which is theoretically impossible because it is endothermic, and would be attended by absorption of heat. But heat external to the system intervenes, and acts either by depolymerising the carbon into a simpler form which can combine with oxygen of the CO_2 with evolution of heat, or by dissociating carbonic anhydride sets oxygen free which combines with the carbon. Reduction of oxide of iron in the blast furnace is mainly effected by carbonic oxide according to the well-known reaction

$$Fe_2O_3 + 3CO = 2Fe + 3CO_2.$$

But the gas issuing from a blast furnace contains carbonic oxide, an important source of heat. The view that this loss of carbonic oxide was due to the fact that the contact of the ore and the reducing gas was not sufficiently prolonged, led to a great increase in the height of blast furnaces, but without, as Grüner showed, diminishing the proportion of carbonic oxide escaping from the throat. The reduction of an iron ore by carbonic oxide only takes place within certain well-defined limits, and a knowledge of the laws of chemical equilibrium would have saved thousands and thousands of pounds which have been wasted in building unduly high furnaces. I would add that large sums have also been sacrificed in the vain attempt to smelt oxide of zinc in the blast furnace, for which operation patents have frequently been sought, in ignorance or defiance of the readiness with which the inverse action occurs, so that the reducing action of carbon on oxide of zinc may be balanced by the re-oxidation of the reduced zinc by carbonic anhydride, which is the product of the reduction. A further instance may be borrowed from an electro-chemical process which has been adopted for obtaining alloys of aluminium. As is well known, all attempts to effect the direct reduction of alumina by carbon have failed, because the reaction

$$2(Al_2O_3) + 3C = 4Al + 3CO_2$$

requires 783·2 calories, while only 291 calories would result from the conversion of carbon into carbonic anhydride, therefore the reaction cannot be effected; but in Cowle's process aluminium is nevertheless liberated when alumina is mixed with charcoal and strongly heated by the passage of an electric current. This result is due, not to a simple reduction of alumina, but to its dissociation at the high temperature produced by the passage of a current of 1,600 amperes between carbon poles, the liberated aluminium being at once removed from the system by metallic copper which is simultaneously present and may not be without action itself.

An instance of the importance of these considerations is presented in the manufacture of steel by the basic process. Much care is devoted to obtaining conditions which will ensure not only the elimination, but the order of the disappearance of the impurities from the molten pig-iron. In the basic process as conducted in the closed converter, the phosphorus does not

disappear until the carbon has left the fluid bath, whilst, when the open-hearth furnace is used, the elimination of the phosphorus may be effected before that of the carbon, and it is asserted that if the carbon goes before the phosphorus is got rid of, a further addition of carbon is necessary. A curious and subtle case of chemical equilibrium is here presented. In the open-hearth furnace and Bessemer converter respectively, the temperatures and pressures are different, and the conditions as to the presentation of oxygen to the fluid bath are not the same. The result is that the relative rates of oxidation of the phosphorus and carbon are different in the two cases, although in either case, with a given method of working, there must be a ratio between the phosphorus and carbon in which they disappear simultaneously. The industrial bearing of the question is very remarkable. In the basic Bessemer process the tendency of the phosphorus to linger in the bath renders an "after-blow" necessary, it may be only of a few seconds' duration, but much iron is nevertheless burnt and wasted, and Mr. Gilchrist tells me that if this after-blow could be avoided, a saving of some 6 per cent. of the yield of steel would be effected annually, the value of which, at the present rate of output and price of steel, is no less than a quarter of a million sterling.

The larger loss of sulphur by the steel in the converter than that which occurs in the open-hearth furnace, and the increase in the percentage of manganese, which leaves the slag and returns to the bath of metal in the converter at the end of the "blow," will probably be traced to the disturbance of equilibrium which attends very slight variations in the conditions, especially as regards temperature and pressure, under which the operations are conducted.

In the blast furnace the reducing action must be greatly dependent on the rate at which alkaline cyanides are formed, and Hempel has recently shown, by the aid of well-devised experiments, that the quantity of cyanides which may be obtained at a high temperature from carbon, nitrogen, and alkaline oxides, increases as the pressure becomes greater.

Metallurgical chemistry is, in fact, a special branch of chemical science which does not come within the ordinary sphere of the academic teaching of chemistry. It is often urged that metallurgical practice depends upon the application of chemical principles which are well taught in every large centre of instruction in this country, but a long series of chemical reactions exist which are of vital importance to the metallurgist, though they are not set forth in any British manual of chemistry, nor are dealt with in courses of purely chemical lectures. I feel bound to insist upon this point, because, as Examiner in Metallurgy for the Science and Art Department, I find that purely analytical and laboratory methods are so often given in the belief that they are applicable to processes conducted on a large scale and at high temperatures.

We are told that technical instruction should be kept apart from scientific education, which consists in preparing the student to apply the results of past experience in dealing with entirely new sets of conditions, but it can be shown that there is a whole side of metallurgical teaching which is truly educational, and leads students to acquire the habit of scientific thought as surely as the investigation of any other branch of knowledge.

It is, in fact, hardly possible in a course of theoretical chemistry to devote much attention to specific cases of industrial practice in which reactions

are incomplete, because they are limited by the presence of bodies that cannot be directly eliminated from the chemical system. Take, for instance, the long series of reactions studied by Plattner, who published the results of his investigations in his celebrated treatise, "Die Metallurgische Röstprozesse," Freiberg, 1856, whose work I have chosen as a starting-point on account of our presence in South Wales near the great copper smelting district of Swansea. A complex sulphide, of which copper is the main metallic constituent, contains some 50 ounces of silver to the ton. The problem may be supposed for the present to be limited to the extraction of the precious metal from the mass in which it is hidden, and the student deriving his knowledge from an excellent modern chemical treatise would find the case thus stated :—

"Ziervogel's process depends upon the fact that when argentiferous copper pyrites is roasted, the copper and iron sulphides are converted into insoluble oxides, whilst the silver is converted into a soluble sulphate which is dissolved out by lixiviating the roasted ore with hot water, the silver being readily precipitated from this solution in the metallic state."

It is certain that if an observant, chemically-trained student visited a silver extraction works, and possessed sufficient analytical skill to enable him to secure evidence as to the changes that occur, he would find a set of facts which his training had not enabled him to predict, and he would establish the existence of a set of reactions to the nature of which his chemical reading had hardly given him a clue. The process to be considered is a simple one, but it is typical, and applies to a large proportion of the 7,000,000 ounces of silver annually obtained in the world from cupriferous compounds. He would be confronted with a ton or more of finely divided material spread in a thin layer over the bed of a reverberatory furnace. Suppose the material is what is known as a complex regulus as imported into Swansea or produced at Freiberg, to which are added rich native sulphides. The mixture then consists of sulphides mainly of iron and copper, with some sulphide of lead, and contains 50 or 60 ounces of silver to the ton, and a few grains of gold. It may also contain small quantites of arsenic and antimony as arsenides, antimonides, and sulpho-salts, usually with copper as a base.

The temperature of the furnace in which the operation is to be performed is gradually raised, the atmosphere being an oxidising one. The first effect of the elevation of the temperature is to distil off sulphur, reducing the sulphides to a lower stage of sulphurisation. This sulphur burns in the furnace atmosphere to sulphurous anhydride (SO_2), and coming in contact with the material undergoing oxidation is converted into sulphuric anhydride (SO_3). It should be noted that the material of the brickwork does not intervene in the reactions, except by its presence as a hot porous mass, but its influence is, nevertheless, considerable. The roasting of these sulphides presents a good case for the study of chemical equilibrium. As soon as the sulphurous anhydride reaches a certain tension the oxidation of the sulphide is arrested, even though an excess of oxygen be present, and the oxidation is not resumed until the action of the draught changes the conditions of the atmosphere of the furnace, when the lower sulphides remaining are slowly oxidised, the copper sulphide being converted into copper sulphate mainly by the intervention of the sulphuric anhydride formed as indicated. Probably by far the greater part of the iron sulphide only becomes sulphate for a very brief period, being

decomposed into the oxides of iron, mainly ferric oxide, the sulphur passing off. Any silver sulphide that is present would have been converted into metallic silver at the outset were it not for the simultaneous presence of other sulphides, notably those of copper and of iron, which enables the silver sulphide to become converted into sulphate. The lead sulphide is also converted into sulphate at this low temperature. The heat is now raised still further with a view to split up the sulphate of copper, the decomposition of which leaves oxide of copper. If, as in this case, the bases are weak, the sulphuric anhydride escapes mainly as such; but when the sulphates of stronger bases are decomposed the sulphuric anhydride is to a great extent decomposed into a mixture of sulphurous anhydride and oxygen. The sulphuric anhydride, resulting from the decomposition of this copper sulphate, converts the silver into sulphate, and maintains it as such, just as, in turn, at a lower temperature, the copper itself had been maintained in the form of sulphate by the sulphuric anhydride eliminated from the iron sulphide. When only a little of the copper sulphate remains undecomposed, the silver sulphate begins to split up, and the furnace charge must, therefore, be immediately withdrawn, or the whole of the silver sulphate would be converted into metallic silver, partly by the direct action of heat alone, and partly by reactions such as those shown in the following equations:—

$$Ag_2SO_4 + 4Fe_3O_4 = 2Ag + 6Fe_2O_3 + SO_2$$
$$Ag_2SO_4 + Cu_2O = 2Ag + CuSO_4 + CuO.$$

If the charge were not withdrawn, the silver would thus be effectually removed from the solvent action of water, and the smelter's efforts would have failed entirely. The charge still contains lead sulphate, which cannot be completely decomposed at any temperature attainable in the roasting furnace, except in the presence of silica, and it is well to leave it where it is if the residue has subsequently to be smelted with a view to the extraction of the gold. The elimination of arsenic and antimony gives rise to problems of much interest, and again confronts the smelter with a case of chemical equilibrium. For the sake of brevity it will be well for the present to limit the consideration to the removal of antimony, which may be supposed to be present as sulphide. Some sulphide of antimony is distilled off, but this is not its only mode of escape. An attempt to remove antimony by rapid oxidation would be attended with the danger of converting it into insoluble antimoniates of the metals present in the charge. In the early stages of the roasting it is, therefore, necessary to employ a very low temperature, and the presence of steam is found to be useful as a source of hydrogen, which removes sulphur as hydrogen sulphide, the gas being freely evolved. The reaction

$$Sb_2S_3 + 3H_2 = 3H_2S + 2Sb$$

between hydrogen and sulphide of antimony is, however, endothermic, and could not, therefore, take place without the aid which is afforded by external heat. The facts appear to be as follows:—Sulphide of antimony, when heated, dissociates, and the tension of the sulphur vapour would produce a state of equilibrium if the sulphur thus liberated were not seized by the hydrogen and removed from the system. The equilibrium is thus destroyed and fresh sulphide is dissociated. The general result being that the equilibrium of the

system is continually restored and destroyed until the sulphide is decomposed. The antimony combines with oxygen and escapes as volatile oxide, as does also the arsenic, a portion of which is volatilised as sulphide

The main object of the process which has been considered is the formation of soluble sulphate of silver. If arsenic and antimony have not been eliminated, their presence at the end of the operation will be specially inconvenient, as they give rise to the formation of arseniate and antimoniate of silver, insoluble in water, which may necessitate the treatment of the residues by an entirely different process from that which has hitherto been considered.

It will have been evident that effecting this series of changes demands the exercise of the utmost skill, care, and patience. The operations beginning at a dull red heat, or a temperature of some 500°, are completed at 700°, within a range, that is, of 200°. Judicious stirring has been necessary to prevent the formation of crusts of sulphates, which would impede the reactions, and, as has been shown, an undue elevation of temperature within a very limited range would, at any stage, have been fatal to the success of the operation. It is difficult to appreciate too highly the delicacy of sight and touch which enables an operator to judge by the aid of rough tests, but mainly from the tint of the streak revealed when the mass is rabbled, whether any particular stage has or has not been reached, and it will be obvious that the requisite skill is acquired solely by observation and experiment. The technical instructor may impart information as to the routine to be followed, and the appearances to be observed, but scientific knowledge of a high order can alone enable the operator to contend with the disturbing influences introduced by the presence of unexpected elements or by untoward variations in temperature. In the training of a metallurgist it is impossible to separate education from instruction, and the above description of a very ordinary operation will show the intimate relations between science and practice which are characteristic of metallurgical operations. Practice is dependent on science for its advancement, but scientific workers too often hesitate to attack metallurgical problems, and to devote the resources of modern investigation to their solution, because they are not aware of the great interest of the physical and chemical problems which are connected with many very simple metallurgical processes, especially with those that are conducted at high temperatures.

Proceeding yet one step further, suppose that the copper smelter takes possession of the residual mass, consisting mainly of oxide of copper, he would smelt it with fresh sulphide ores and obtain, as a slag from the earthy matters of the ore, a ferrous silicate containing some small proportion of copper. The displacement of the copper from this silicate may be effected by fusing it with sulphide of iron, a fusible sulphide of iron and copper being formed which readily separates from the slag. By this reaction some 20,000 tons of copper are added to the world's annual production. Proceeding a step further, suppose the smelter to have reduced his copper to the metallic state. If arsenic had been originally present in the ore, and had not been eliminated entirely in the roasting, extraordinary difficulties would be met with in the later stages of the process, in extracting small quantities of arsenic which resist the smelter's efforts. Copper, moreover, containing above 1 per cent. of arsenic cannot be "overpoled," as the presence of arsenic hinders the action of gases on the copper. The amount

of arsenic which the copper smelter has to remove may vary from mere traces up to 1 per cent., and if the copper is destined for the use of the electrical engineer, he will insist on its being as pure as possible, for the presence of a trace of arsenic would materially increase the electrical resistance of the copper, and would be fatal to its use in submarine telegraphy. If, on the other hand, the copper is intended for the maker of locomotive fire-boxes, he will encourage the retention of small quantities of arsenic, as it is found to actually increase the endurance of the copper, and the smelter will in such a case have no inducement to employ the basic furnace lining which Mr. Gilchrist has offered him, nor will he care to use the special methods for the removal of arsenic with which he is familiar. It may all seem simple enough, but the modern process of copper smelting has been laboriously built up, and has a long and interesting pedigree which may be traced to at least the eighth century, when Geber described the regulus "coarse metal" as being "black mixed with livid," and our familiar "blue metal" as being "of a most clean and pleasant violet colour," and indicated the reason for the difference.

(3) The foregoing instances have been given to indicate the general nature of metallurgical chemistry. It will be well now to show how the great advances in metallurgical practice have been made in the past, with a view to ascertain what principles should guide us in the future.

It is a grave mistake to suppose that in industry, any more than in art, national advance takes place always under the guidance of a master possessed of some new gift of invention, yet we have been reminded that we are apt to be reverent to these alone, as if the nation had been unprogressive, and suddenly awakened by the genius of one man. The way for any great technical advance is prepared by the patient acquisition of facts by investigators of pure science. Whether the investigators are few or many, and consequently whether progress is slow or rapid, will depend in no small measure on the spirit of the nation as a whole. A genius whose practical order of mind enables him to make some great invention suddenly arises, apparently by chance, but his coming will, in most cases, be found to have "followed hard upon" the discovery by some scientific worker of an important fact, or even the accurate determination of a set of physical constants. No elaborate monograph need have reached the practical man—a newspaper paragraph, or a lecture at a Mechanics' Institute may have been sufficient to give him the necessary impulse; but the possessors of minds which are essentially practical often forget how valuable to them have been the fragments of knowledge they have so insensibly acquired that they are almost unconscious of having received any external aid.

The investigating and the industrial faculty are sometimes, though rarely, united in one individual. Rapid advance is often made by those who are untrammelled by a burden of precedent, but it should be remembered that though the few successes, which have been attained in the course of ignorant practice, may come into prominence, none of the countless failures are seen.

I would briefly direct attention to certain processes which have been adopted since the year 1849, when Dr. Percy presided over this Section at Birmingham, a great metallurgical centre. In that year the President of the Association made a reference to metallurgy, a very brief one, for Dr.

Robinson only said "the manufacture of iron has been augmented six-fold by the use of the puddling furnace and the hot-blast, both gifts of theory"; and so, it may be added, are most of the important processes which have since been devised. Take the greatest metallurgical advance of all, the Bessemer process, which has probably done more than any other to promote the material advance of all countries. It was first communicated to the world at the Cheltenham Meeting of the British Association, 1856. Its nature is well known, and I need only say that it depends on the fact that when air is blown through a bath of impure molten iron, sufficient heat is evolved by the rapid combustion of silicon, manganese, and carbon to maintain the bath fluid after these elements have been eliminated, there being no external source of heat, as there is in the puddling furnace or the refinery hearth. We have recently been told that at an early and perilous stage of the Bessemer process confidence in the experiments was restored by the observation that the temperature of the "blown" metal contained in a crucible was higher than that of the furnace in which it was placed. The historian of the future will not fail to record that the way for the Bessemer process had been prepared by the theoretical work of Andrews, 1848, and of Favre and Silbermann, 1852, whose work on the calorific power of various elements showed that silicon and phosphorus might be utilised as fuel, because great heat is engendered by their combustion.

The basic process for removing phosphorus, a process of great national importance, the development of which we owe to Thomas and Gilchrist, is entirely the outcome of purely theoretical teaching, in connection with which the names of Grüner and Percy deserve special mention. In the other great group of processes for the production of steel, those in which Siemens' regenerative furnace is employed, we have the direct influence of a highly trained theorist, who concluded his address as President of this Association in 1882 by reminding us that "in the great workshop of nature there is no line of demarcation to be drawn between the most exalted speculation and commonplace practice." The recent introduction of the method of heating by radiation is, of course, the result of purely theoretical considerations.

The progress in the methods of extracting the precious metals has been very great, both on the chemical and engineering sides, but it is curious that in the metallurgy of gold and silver many ancient processes survive which were arrived at empirically—a noteworthy exception being presented by the chlorine process for refining gold, by the aid of which many millions sterling of gold have been purified. The late Mr. H. B. Miller based this process for separating silver from gold on the knowledge of the fact that chloride of gold cannot exist at a bright red heat. The tension of dissociation of chloride of gold is high, but the precious metal is not carried forward by the gaseous stream, at least not while chloride of silver is being formed.

The influence of scientific investigation is, however, more evident in that portion of the metallurgic art which deals with the adaptation of metals for use, rather than with their actual extraction from the ores.

Only sixteen years ago Sir Nathaniel Barnaby, then Director of Naval Construction, wrote, "our distrust of steel is so great that the material may be said to be altogether unused by private shipbuilders . . . and marine engineers appear to be equally afraid of it." He adds, "the question we have to put to the steel makers is, what are our prospects of obtaining a

material which we can use without such delicate manipulation and so much fear and trembling?" All this is changed, for, as Mr. Elgar informs me, in the year ending on June 30 last, no less than 401 ships, of three-quarters of a million gross tonnage, were being built of steel in the United Kingdom.

Why is it, then, that steel has become the material on which we rely for our ships and for our national defence, and of which such a splendid structure as the Forth Bridge is constructed. It is because side by side with great improvement in the quality of certain varieties of steel, which is the result of using the open-hearth process, elaborate researches have shown what is the most suitable mechanical and thermal treatment for the metal; but the adaptation of steel for industrial use is only typical, as the interest in this branch of metallurgy generally appears for the moment to be centred in the question whether metals can, like many metalloids, pass under the application of heat or mechanical stress from a normal state to an allotropic one, or whether metals may even exist in numerous isomeric states.

It is impossible to deal historically with the subject now further than by stating that the belief in more than one "modification" is old and widespread, and was expressed by Paracelsus, who thought that copper "contains in itself its female," which could be isolated, so as to give "two metals" . . . "different in their fusion and malleability" as steel and iron differ. Within the last few years Schützenberger has shown that two modifications of copper can exist, the normal one having a density of 8·95, while that of the allotropic modification is only 8·0, and is, moreover, rapidly attacked by dilute nitric acid which is without action on ordinary copper. It may be added that Lord Rayleigh's plea for the investigation of the simpler chemical reactions has been partly met, in the case of copper, by the experiments conducted by V. H. Veley on the conditions of chemical change between nitric acid and certain metals.

Bergmann, 1781, actually calls iron polymorphous, and says that it plays the part of many metals. "Adeo ut jure dici queat polymorphum ferrum plurium simul metallorum vices sustinere." Osmond has recently demonstrated the fact that at least two modifications of iron must exist.

Professor Spring, of Liége, has given evidence that in cooling lead-tin alloys polymerisation may take place after the alloys have become solid, and it seems to be admitted that the same cause underlies both polymerisation and allotropy. The phenomenon of allotropy is dependent upon the number of the atoms in each molecule, but we are at present far from being able to say what degree of importance is to be attached to the relative distance between the atoms of a metal or to the "position of one and the same atom" in a metallic molecule, whether the metal be alloyed or free; and it must be admitted that in this respect organic chemistry is far in advance of metallurgic chemistry. I cannot, as yet, state what is the atomic grouping in the brilliantly-coloured gold-aluminium alloy, $AuAl_2$, which I have had the good fortune to discover, but, in it, the gold is probably present in the same state as that in which it occurs in the "purple of Cassius."

Much valuable information on the important question of allotropy in metals has already been gathered by Pionchon, Ditte, Moissan, Le Chatelier, and Osmond, but reference can only be made to the work of the two latter. Le Chatelier concludes that in metals which do not undergo molecular transformation the electrical resistance increases proportionally to the temperature.

The same law holds good for other metals at temperatures above that at which their last change takes place, for example in the case of nickel above 340°, and in that of iron above 850°.

It is probable that minute quantities of foreign matter which profoundly modify the structure of masses of metal also induce allotropic changes. In the case of the remarkable action of impurities upon pure gold I have suggested that the modifications which are produced may have direct connection with the periodic law of Mendeléef, and that the causes of the specific variations in the properties of iron and steel may thus be explained. The question is of great industrial importance, especially in the case of iron; and Osmond, whose excellent work I have already brought before the members of this Association, in a lecture delivered at Newcastle in 1889, has specially studied the influence upon iron exerted by certain elements. He shows that elements whose atomic volumes are smaller than that of iron delay, during the cooling of a mass of iron from a red heat, the change of the β, or hard variety of iron, to the α, or soft variety. On the other hand, elements whose atomic volumes are greater than that of iron tend to hasten the change of β to α iron. It is, however, unnecessary to dwell upon this subject, as it was dealt with last year in the Address of the President of the Association.

It may be added that the recent use of nickel-steel for armour plate and the advocacy of the use of copper-steel for certain purposes, is the industrial justification of my own views as to the influence of the atomic volume of an added element on the mechanical properties of iron, and it is remarkable that the two bodies, silicon and aluminium, the properties of which when in a free state are so totally different, should, nevertheless, when they are alloyed with iron, affect it in the same way. Silicon and aluminium have almost the same atomic volumes.

The consequences of allotropic changes which result in alteration of structure are very great. The case of the tin regimental buttons which fell into a shapeless heap when exposed to the rigorous winter at St. Petersburg is well known. The recent remarkable discovery by Hopkinson of the changes in the density of nickel-steel (containing 22 per cent. of nickel) which are produced by cooling to $-30°$, affords another instance. This variety of steel, after being frozen, is readily magnetisable, although it was not so before; its density, moreover, is permanently reduced by no less than 2 per cent. by the exposure to cold; and it is startling to contemplate the effect which would be produced by a visit to the arctic regions of a ship of war built in a temperate climate of ordinary steel clad with some 3,000 tons of such nickel-steel armour; the shearing which would result from the expansion of the armour by exposure to cold would destroy the ship. Experimental compound armour-plates have been made faced with 25 per cent. nickel-steel, but it remains to be seen whether a similar though lessened effect would be produced on the steel containing 5 to 7 per cent. of nickel, specially studied by J. Riley, the use of which is warmly advocated for defensive purposes. Further information as to the molecular condition of nickel-steel has within the last few weeks been given by Mercadier, who has shown that alloying iron with 25 per cent. of nickel renders the metal isotropic.

The molecular behaviour of alloys is indeed most interesting. W. Spring has shown, in a long series of investigations, that alloys may be formed at the ordinary temperature, provided that minute particles of the constituent

metals are submitted to great pressure. W. Hallock has recently given strong evidence in favour of the view that an alloy can be produced from its constituent metals with but slight pressure if the temperature to which the mass is submitted be above the melting point of the alloy, even though it be far below the melting point of the most easily fusible constituent. A further instance is thus afforded of the fact that a variation of either temperature or pressure will effect the union of solids. It may be added that B. C. Damien is attempting to determine what variation in the melting point of alloys is produced by fusing them under a pressure of 200 atmospheres. Italian physicists are also working on the compressibility of metals, and F. Boggio-Lera has recently established the existence of an interesting relation between the coefficient of cubic compressibility, the specific gravity, and the atomic weight of metals.

Few questions are more important than the measurement of very high temperatures. Within the last few years H. le Chatelier has given us a thermocouple of platinum with platinum containing 10 per cent. of rhodium, by the aid of which the problem of the measurement of high temperatures has been greatly simplified. A trustworthy pyrometer is now at hand for daily use in works, and the liberality of the Institution of Mechanical Engineers has enabled me to conduct an investigation which has resulted in the adoption of a simple appliance for obtaining, in the form of curves, photographic records of the cooling of masses of metal. A report on the subject has already been submitted to a Committee, of which the Director-General of Ordnance Factories is the Chairman; and Dr. Anderson, to whom I am indebted for valuable assistance and advice, intends to add this new method for obtaining autographic curves of pyrometric measurements to the numerous self-recording appliances used in the Government factories which he controls. It has proved to be easy to ascertain, by the aid of this pyrometer, what thermal changes take place during the cooling of molten masses of alloys, and it is possible to compare the rate of cooling of a white-hot steel ingot at definite positions situated respectively near its surface and at its centre, and thus to solve a problem which has hitherto been considered to be beyond the range of ordinary experimental methods. Some of the curves already obtained are of much interest, and will be submitted to the Section. It is probable that the form of the curve which represents the solidification and cooling of a mass of molten metal affords an exceedingly delicate indication as to its purity.

Prof. H. E. Armstrong holds that the molecules of a metal can unite to form complexes with powers of coherence which vary with the presence of impurity. Crookes, by a recent beautiful investigation, has taught us how electrical evaporation of solid metals may be set up in vacuo, and has shown that even an alloy may be decomposed by such means. We may hope that such work will enable us to understand the principles on which the strength of materials depends.

Before leaving the consideration of questions connected with the molecular constitution of metals, I would specially refer to the excellent work of Heycock and Neville, who have extended to certain metals with low melting points Raoult's investigations on the effect of impurity on the lowering of the

freezing-point of solids. With the aid of one of my own students, H. C. Jenkins, I have further extended the experiments by studying the effect of impurity on the freezing-point of gold. Ramsay, by adopting Raoult's vapour-pressure method, has been led to the conclusion that when in solution in mercury the atom of a metal is, as a rule, identical with its molecule. The important research on the liquation of alloys has been extended by E. Matthey to the platinum-gold and palladium-gold series, in which the manipulation presented many difficulties; and E. J. Ball has studied the cases presented by the antimony-copper-lead series. Dr. Alder Wright has continued his own important investigation upon ternary alloys, and A. P. Laurie has worked on the electromotive force of the copper-zinc and copper-tin and gold-tin series, a field of research which promises fruitful results.

In no direction is advance more marked than in the mechanical testing of metals, in which branch of investigation this country, guided by Kirkaldy, undoubtedly took the leading part, and in connection with which Kennedy and Unwin have established world-wide reputations. I would also specially mention the work which has been carried on at the Government testing works at Berlin under Dr. Wedding, and the elaborate investigations conducted at the Watertown Arsenal, Massachusetts, not to mention the numerous continental testing laboratories directed by such men as Bauschinger, Jenny, and Tetmajer. Perhaps the most important recent work is that described by Prof. Martens, of Berlin, on the influence of heat on the strength of iron.

I might have dwelt at length on all these matters without doing half the service to metallurgy that I hope to render by earnestly pleading for the more extended teaching of the subject throughout the country, and for better laboratories, arranged on the model of engineering laboratories, in which the teaching is conducted with the aid of complete, though small, "plant." The Science and Art Department has done great and lasting service by directing that metallurgy shall be taught practically, but much remains to be done. With regard to laboratories in works, which are too often mere sheds, placed, say, behind the boiler-house, when may we hope to rival the German chemical firm which has recently spent £19,000 upon its laboratories, in which research will be vigorously conducted? There is hardly any branch of inorganic chemistry which the metallurgist can afford to neglect, while many branches, both of physics and mechanics, are of utmost importance to him.

The wide range of study upon which a metallurgical student is rightly expected to enter is leading, it is to be feared, to diminution in the time devoted to analytical chemistry, and this most serious question should be pressed upon the attention of all who are responsible for the training of our future chemists. There can be no question that sufficient importance is not attached to the estimation of "traces," an analysis being considered to be satisfactory if the constituents found add up to 99·9, although a knowledge as to what elements represent the missing 0·1 may be more useful in affording an explanation of the defects in a material than all the rest of the analysis. This matter is of growing interest to practical men, and may explain their marked preference for chemists who have been trained in works, to those who have been educated in a college laboratory.

The necessity for affording public instruction in mining and metallurgy,

with a view to the full development of the mineral wealth of a nation, is well known. The issues at stake are so vast, that in this country it was considered desirable to provide a centre of instruction in which the teaching of mining and metallurgy should not be left to private enterprise or even entrusted to a corporation, but should be under the direct control of the Government. With this end in view, the Royal School of Mines was founded in 1851, and has thus supplied a body of well-trained men who have done excellent service for the country and her colonies. The Government has recently taken a step in advance, and has further recognised the national importance of the teaching of mining and metallurgy by directing that the School of Mines shall be incorporated with the Royal College of Science, which is, I believe, destined to lead the scientific education of the nation.

It is to be feared that as regards metalliferous mining, other than that relating to iron, our country has seen its best days, but the extraordinary mineral wealth of our colonies has recently been admirably described by my colleague, Prof. Le Neve Foster, in the inaugural lecture he delivered early in the present year on his appointment to the chair so long held by Sir Warington Smyth. We shall, however, be able to rightly estimate the value of our birthright when the Imperial Institute is opened next year, and the nation will have reason to be grateful to Sir Frederick Abel for the care he is devoting to the development of this great institution, which will become the visible exponent of the splendours of our Indian and Colonial resources, as well as a centre of information.

The rapid growth of technical literature renders it unnecessary for a president of a Section to devote his address to recording the progress of the subject he represents. As regards the most important part of our national metallurgy, this has, moreover, been admirably done by successive Presidents of the Iron and Steel Institute, but it may have been expected that references would have been made to the main processes which have been adopted since Percy occupied this chair in 1849. I have not done so, because an enumeration of the processes would have been wholly inadequate, and a description of them impossible in the time at my disposal. Nevertheless, it may be well to remind the Section of a few of the more prominent additions the art has received in the last half century, and to offer a few statements to show the magnitude on which operations are conducted. As regards iron, in the last twenty-five years the price of steel has been reduced from £55 per ton to £5 per ton, but, after giving the world the inestimable boon of cheap steel by the labours of Bessemer and of Siemens, we were somewhat slow to accept the teaching of experiment as to the best method of treating the new material; on the other hand, Hadfield has brought manganese steel and aluminium steel within the reach of the manufacturer, and J. Riley has done much to develop the use of nickel steel.

In the case of copper, we have mainly contributed to extraordinary development of wet processes for its extraction from poor sulphides, and have met the great demands for pure metal by the wide adoption of electrolytic processes.

As regards the precious metals, this country is well to the front, for Great Britain and her Colonies produce about 38 per cent. of the gold supply of the world;[1] and it may be well to add, as an indication of the scale on which

[1] In 1911 the British Empire produced 56·7 per cent. of the world's output of gold (Bedford M'Neill, *Inst. Min. and Met.*, 1913).

operations are conducted, that in London alone 1 ton of gold and 5 tons of silver bullion can easily be refined in a day. In the case of the platinum industry we owe its extraordinary development to the skill and enterprise of successive members of the firm of Johnson, Matthey & Co., who in later years have based their operations upon the results of the investigations of Deville and Debray. Some indication of the value of the material dealt with may be gathered from the statement that two and a half hundred weight of platinum may easily be melted in a single charge, and that the firm, in one operation, extracted a mass of palladium valued at £30,000 from the gold-platinum ore actually worth more than a million sterling.

I wish it were possible to record the services of those who have advanced metallurgy in connection with this Association, but the limitations of time render it difficult to do more than refer to some honoured names of past Presidents of this Section. Michael Faraday, President of this Section in 1837 and 1846, prepared the first specimen of nickel steel, an alloy which seems to have so promising a future, but we may hardly claim him as a metallurgist; nor should I be justified in referring, in connection with metallurgical research, to my own master, Graham, President of this Section in 1839, and again in 1844, were it not that his experiments on the occlusion of gases by metals have proved to be of such extraordinary practical importance in connection with the metallurgy of iron. Sir Lyon Playfair presided over this Section in 1855, and again in 1859. His work in connection with Bunsen on the composition of blast-furnace gases was published in the Report of this Association in 1847, and formed the earliest of a group of researches, amongst which those of Sir Lowthian Bell proved to be of so much importance. The latter was President of this Section in 1889. Sir F. Abel, President of this Section in 1877, rendered enduring service to the Government by his elaborate metallurgical investigations, in connection with materials used for guns and projectiles, as well as for defensive purposes. I will conclude this section of the address by a tribute to the memory of Percy. He may be said to have created the English literature of metallurgy, to have enriched it with the records of his own observations, and to have revived the love of our countrymen for metallurgical investigation. His valuable collection of specimens, made while Professor at the Royal School of Mines, is now appropriately lodged at South Kensington, and will form a lasting memorial of his labours as a teacher. He exerted very noteworthy influence in guiding the public to a just appreciation of the labours of scientific men, and he lived to see an entire change in the tone of the public press in this respect.

In drawing this address to a close, I would point to the great importance of extending the use of the less known metals. Attention is at present concentrated on the production of aluminium, and reference has already been made to the Cowles process, in which, as in that of Héroult, the reduction of alumina is effected by carbon, at the very high temperature of the electric arc; while, on the other hand, in the Kleiner and similar processes, the electric current acts less as a source of heat than by decomposing a fluid bath, the aluminium being isolated by electrolytic action; and doubtless, in the immediate future, there will be a rapid increase in the number of metallurgical processes that depend on reactions which are set up by submitting chemical systems to electric stress. Incidental reference should be made to the growing importance of sodium, not only in cheapening the

production of aluminium, but as a powerful weapon of research. In 1849, when Percy was President of this Section, magnesium was a curiosity; now its production constitutes a considerable industry. We may confidently expect to see barium and calcium produced on a large scale as soon as their utility has been demonstrated by research. Minerals containing molybdenum are not rare; and the metal could probably be produced as cheaply as tin if a use were to be found for it. The quantities of vanadium and thallium which are available are also far from inconsiderable; but we, as yet, know little of the action of any of these metals when alloyed with others which are in daily use. The field for investigation is vast indeed, for it must be remembered that valuable qualities may be conferred on a mass of metal by a very small quantity of another element. The useful qualities imparted to platinum by iridium are well known. A small quantity of tellurium obliterates the crystalline structure of bismuth; but we have lost an ancient art, which enabled brittle antimony to be cast into useful vessels. Two-tenths per cent. of zirconium increases the strength of gold enormously, while the same amount of bismuth reduces the tenacity to a very low point. Chromium, cobalt, tungsten, titanium, cadmium, zirconium, and lithium are already well known in the arts, and the valuable properties which metallic chromium and tungsten confer upon steel are beginning to be generously recognised, as the last Exhibition at Paris abundantly showed; but as isolated metals we know but little of them. Is the development of the rarer metals to be left to other countries? Means for the prosecution of research are forthcoming, and a rich reward awaits the labours of chemists who could bring themselves to divert their attention, for even a brief period, from the investigation of organic compounds, in order to raise alloys from the obscurity in which they are at present left.

It must not be forgotten that metallurgical enterprise rests on (1) scientific knowledge, (2) capital, and (3) labour, and that if the results of industrial operations are to prove remunerative, much must depend on the relation of these three elements, though it is difficult to determine accurately their relative importance. A modern ironworks may have an army of 10,000 workmen, and commercial success or failure will depend in no small measure on the method adopted in organising the labour. The relations between capital and labour are of so much interest at the present time that I do not hesitate to offer a few words on the subject.

Many examples might be borrowed from metallurgical enterprises in this and other countries to show that their success is often uncertain, and that failure is easily induced by what appear to be comparatively slight causes. Capitalists might consequently tend to select Government securities for investment in preference to metallurgical works, and the labouring population would then severely suffer. It is only reasonable, therefore, that if capitalists are exposed to great risks, they should, in the event of success, receive the greater part of the profits. There is a widespread feeling that the interests of capital and labour must be antagonistic, and as it is impossible to ignore the fact that the conflict between them is giving rise to grave apprehension, it becomes the duty of all who possess influence to strive not merely for peace, but to range themselves on the side of justice and humanity. The great labour question cannot be solved except by assuming as a principle that private ownership must be held inviolable, but it must be admitted that

there was a time when capital had become arbitrary and some kind of united action on the part of workmen was needed in self-defence. If, however, we turn to the action of the leaders of trades' unions in the recent lamentable strikes, we are presented with a picture which many of us can only view as that of tyranny of the most close and oppressive kind, in which individual freedom cannot even be recognised. There are hundreds of owners of works who long to devote themselves to the true welfare of those they employ, but who can do little against the influence of the professional agitator, and are merely saddened by contact with prejudice and ignorance. I believe the view to be correct that some system by which the workman participates in the profits of enterprise will afford the most hope of putting an end to labour disputes, and we are told that profit-sharing tends to destroy the workman's sense of social exclusion from the capitalistic board, and contents him by elevating him from the precarious position of a hired labourer. No pains should, therefore, be spared in perfecting a system of profit-sharing.

Pensions for long service are great aids to patience and fidelity, and very much may be hoped from the fact that strenuous efforts are being made by men really competent to lead. The report of the Labour Commission which is now sitting will be looked for with keen interest. Watchful care over the health, interests, and instruction of the employed is exercised by many owners of works; and in this respect the Dowlais Works, which are being transplanted into your midst at Cardiff, have long presented a noteworthy example. Workmen must not forget that the choice of their own leaders is in their own hands, and on this the future mainly depends. "We may lay it down as a perpetual law that workmen's associations should be so organised and governed as to furnish the best and most suitable means for attaining what is aimed at, that is to say, for helping each individual member to better his condition to the utmost in body, mind, and property." The words will be found in the Encyclical letter which Pope Leo XIII. has recently issued on the "Condition of Labour." To me it is specially interesting that the Bishop of Rome in his forcible appeal again and again cites the opinion of St. Thomas Aquinas, who was a learned chemist as well as a theologian.

Those of us who realise that "the higher mysteries of being, if penetrable at all by human intellect, require other weapons than those of calculation and experiment," should be fully sensible of our individual responsibility. Seeing that the study of the relations between capital and labour involve the consideration of the complex problems of existence, the solution of which is at present hidden from us, we shall feel with Andrew Lang that "where, as a matter of science, we know nothing, we can only utter the message of our temperament." My own leads me to hope that the patriotism of the workmen will prevent them from driving our national industries from these shores, and I would ask those to whom the direction of the metallurgical works of this country is confided, to remember that we have to deal both with metals and with men, and have reason to be grateful to all who extend the boundaries, not only of our knowledge, but also of our sympathy.

[illegible]

Metallurgical Laboratory, Royal School of Mines (Jermyn Street, 1877).

From an Oil Painting.

TRIBUTE TO DR. JOHN PERCY, M.D., F.R.S.[1]

John Percy, M.D., who died on the 19th of June last [1889], was born at Nottingham on the 23rd of March, 1817. At an early age he entered the Medical School of the University of Edinburgh, where at twenty-one he took the degree of M.D. He then studied in Paris, making the acquaintance of the leading French chemists of the time, who doubtless directed his mind towards the line of work to which his life was mainly devoted. He practised medicine at Birmingham for a few years, where, coming in contact with directors and managers of works, he was led to take special interest in metallurgy. It is, perhaps, worth remembering that the connection between therapeutics and metallurgy has been traditional, and that the critical period of both was the middle of the sixteenth century, when Paracelsus attempted to introduce order into the science of medicine and Georgius Agricola strove to establish the art of metallurgy on a sound basis.

Dr. Percy's first paper was entitled a "Notice of a New Hydrated Phosphate of Lime." It was followed by other papers on medical subjects, but such work soon gave place to the systematic study of metallurgy, in which he might fairly say with an old writer: "An indefatigable labour, the closest inspection, and hands that were not afraid of the blackness of charcoal" had been his "chief masters." There was, indeed, little else than his own patient research to guide him, for the literature of metallurgy up to the time he wrote was sparse in the extreme, as may be gathered from the fact that when Cramer, himself a doctor of medicine, published in 1754 his "list of the chief English authors (about thirty in all) who have treated of minerals and metals," none had written a treatise of metallurgy worthy of the name, though there were many detached monographs of value and a few papers in the *Philosophical Transactions of the Royal Society*. In the period which elapsed, nearly a century, between the publication of Cramer's book and the time when Dr. Percy accepted the Chair of Metallurgy in the Royal School of Mines and began to teach, the most noteworthy contributions to metallurgical literature were Bishop Watson's Essays. These appeared in 1782, and are fragmentary, but, as Dr. Percy said, "are elegantly and lucidly composed, and I never take them up but with increasing pleasure." In 1861 Dr. Percy published the first volume of his treatise on "Metallurgy," which he dedicated "with sincere respect and affectionate regard" to Faraday. This work, which he calls the "task of his life," developed into a series of volumes containing 3,500 octavo pages. It is on this treatise that his reputation mainly rests, and we cannot doubt but that it will be enduring. The writings of Pliny in the first century, of Geber in the eighth, and of Agricola in the sixteenth, may still be read with profit side by side with the modern work of Karsten, Gay-Lussac, Berzelius, Le Play, Plattner, Deville, and Holley, and it is with these metallurgists that Percy takes his place. His writings differ in many ways from those of his predecessors in any country. He was forcibly impressed with the fact that metallurgical problems demand for their successful investigation the exercise of the highest analytical skill, and involve considerations worthy of those who delight in transcendental inquiries. He effectively

[1] *Proc. Roy. Soc.*, xlvi., 1889.

[*To face page* 128.

Metallurgical Laboratory, Royal School of Mines (Jermyn Street, 1877).

From an Oil Painting.

quotes Réaumur's remark, "l'utile bien considéré a toujours du curieux, et il est rare que le curieux bien suivi ne mène pas à l'utile."

The distinctive character of his metallurgical treatises arises from the care with which he examined the relations of the metals to other elements and to each other. While his predecessors unhesitatingly accepted the statements of earlier writers or showed a tendency to deduce from analogy what these relations would be, he made the properties of metallic compounds the subject of careful experiment and embodied the results in his books, which form a record of great value, and one that teems with suggestions for future investigators. The excellence of the chemical portions of his books gives them great value as works of reference quite apart from the accurate and elaborate descriptions they contain of typical metallurgical processes. These were in all cases prepared by the best men he could find, usually his own students, who were actually engaged in conducting the operations they describe. Such aid was always fully acknowledged. One remarkable feature of these books is that almost every woodcut may be considered to be an accurate though small mechanical drawing, and it is only measurable drawings of this kind which are really useful in practice. In criticising his writings it may perhaps be said that his dread of mere empiricism and his intolerance of inaccuracy often led him to magnify points which now seem to be somewhat trivial, and he sometimes withholds the expression of his own opinion when the reader has fairly a right to expect his guidance and would be grateful for the support of his authority.

Of all his work, that relating to iron and steel is perhaps the most important, and it began early in his metallurgical career with an elaborate piece of analytical work. The first International Exhibition, of 1851, contained a very extensive and highly interesting series of British iron ores, collected with great labour and at considerable expense by Dr. Percy's friend, Mr. H. S. Bakewell, of Dudley, and afterwards presented by him to the Geological Museum in Jermyn Street. Mr. Bakewell placed at Dr. Percy's disposal the sum of £500 towards defraying the cost of analysing the more important of these ores. The work was completed by Dr. Percy with but slender aid from Government, and the results are embodied in his treatise on Iron and Steel, which was published in 1864. They have rightly been described as the first serious attempt at a survey of our national resources as regards ores of iron. With regard to the actual extraction of iron from its ores, his services were not less important. In 1855 the fact was established that pig-iron from the blast furnace contains the greater part of the phosphorus originally present in the ore. Dr. Percy pointed out that phosphorus is not eliminated to a sensible degree in the Bessemer process, as it is in the old process of puddling; and he was of opinion that if the Bessemer process was to be "generally applicable in this country, it must be supplemented by the discovery of a method of producing pig-iron sensibly free from phosphorus and sulphur with the fuel and ores which are now so extensively employed in our blast furnaces." The practical solution of the problem of eliminating phosphorus in the Bessemer converter, and the wide adoption of a process of truly national importance, are the outcome of Dr. Percy's teaching, for the problem was solved by three of his pupils. The delivery of his eloquent address in 1886, as President of the Iron and Steel Institute, fittingly ended the active portion of his labours with regard to these metals.

His most noteworthy addition to practical metallurgical processes was described in a paper written by him in 1848, and published in the same year in a journal called *The Chemist*. A translation of this paper reached a distinguished Austrian, who introduced, at Joachimsthal, the process now known as that of von Patera, which depends on the solubility of chloride of silver in hyposulphite of soda. Early in 1884 this process was modified in America, by Mr. E. H. Russell, in order to render it applicable to ores poor in silver, which also contain a considerable quantity of base metal. Those who have seen this process as now conducted in the Western States of America will appreciate the importance of Dr. Percy's original suggestion. His contributions to our knowledge of metallic alloys were of special value, and he discovered the alloy of copper and aluminium, now known as aluminium-bronze.

He concluded the introductory lecture which he delivered at the Royal School of Mines, more than a quarter of a century ago, by pointing out that "in proportion to the success with which the metallurgic art is practised in this country will the interests of the whole population, directly or indirectly, in no inconsiderable degree be promoted." The recognition of this fact appears to have steadily guided him, and his best services were always at the disposal of the Government and were freely used, as will be seen from the long list of Royal Commissions and Departmental Inquiries upon which he served. The first of these was the Committee appointed, in 1861, by the Secretary of State for War, to inquire into the "Application of Iron for defensive purposes." This continued its labours for four years, and was followed by a Special Committee appointed in 1867, to inquire into "Gibraltar" shields. He was also a member of the Royal Commission appointed in 1871, "to inquire into several matters relative to Coal in the United Kingdom," and of the Royal Commission of 1875, which investigated "the cause of the Spontaneous Combustion of Coal in Ships."

He resigned his chair at the Royal School of Mines in 1879, but he continued to hold the office of Lecturer of Metallurgy to the Advanced Class of Artillery Officers, at Woolwich. He was also Superintendent of the Ventilation, Warming, and Lighting of the Houses of Parliament. In both of these appointments he took great interest until his last illness. Dr. Percy collected with great care a series of metallurgical specimens to illustrate special points of interest relating to the manufacture and uses of metals. "From the study of it," he said, "I have myself derived much instruction. There are no specimens which, in my judgment, are more instructive than such as exhibit defects which have appeared either in the process of manufacture or in the use of metals." This collection was formed while Dr. Percy was at Birmingham and during the period of twenty-nine years he was Lecturer on Metallurgy at the Royal School of Mines. The specimens are of great interest and value, and, as in many cases they represent obsolete processes, no similar specimens could again be obtained. They are all minutely described by labels, many of which bear incidental references to Dr. Percy's Treatise on Metallurgy, to official reports, and to technical literature. It may safely be asserted that no existing metallurgical collection can compare with this in interest and importance. It is fortunate, therefore, that it will not be dispersed, but, in accordance with the wishes of Dr. Percy's family, will be preserved in connection with the School of Mines, where he taught so long, and exhibited to the public at South Kensington, as the "Percy Collection."

The most cursory examination of his writings will serve to show the rigid precision with which he wrote. Sometimes when his sympathy or indignation was aroused he would adopt a more florid though not less effective style, of which it would be difficult to find more characteristic examples than the two extracts here placed in conjunction, both relating to the exhaustion of our national supply of coal, and both being exponents of his patriotic wishes for the welfare of his country. Speaking of a well-known coal-field, he says, "This magnificent bed of coal has been most barbarously treated. The pits have generally been worked by contractors under the superintendence of viewers, called ground bailiffs. In consequence of the rapacity and rascality of many of the former, and of the ignorance, inattention, and fraudulent connivance of many of the latter, an enormous amount of coal has been irremediably lost to the nation." After an interval of ten years he said, in concluding his Presidential Address at the Iron and Steel Institute, "There is a question which must often occur to us, namely, what will Great Britain be when our vast reservoir of material force, coal, is exhausted. . . . The time must come when, in consequence of that exhaustion, Great Britain will cease to be a great manufacturing nation, . . . but, however mournful and unwelcome this proposition may be, we have the satisfaction of knowing that we are now laying the foundation of prosperous and mighty kingdoms in various parts of the world which we hope will be the strongholds of virtue, of order, and of freedom. . . . The glory of old England may, after all, not depart; on the sites of the soot-stained Birminghams and Manchesters new and splendid cities may arise where the merchant princes, of Anglo-Saxon descent, from the remotest parts of the globe shall rejoice to dwell and end their days in peace."

Dr. Percy's public utterances were but few, and the above formed a part of the last of them. He led a retired life and was hardly ever seen at Scientific Societies, though he was frequently at the Athenæum and was well known at the Garrick Club.

He married in June, 1839, Miss Grace Mary Piercy, the only daughter of Mr. J. E. Piercy of Warley Hall, near Birmingham. Those who knew him best feel that the loss of his wife, in 1880, greatly changed him.

Official recognition of his admirable labours there is none to record, but many Scientific Societies and Institutions conferred on him their membership. He was elected a Fellow of the Royal Society in 1847, and served on its Council in 1857-59; he was awarded the Millar Prize of the Institution of Civil Engineers, of which body he was one of the few Honorary Members. He received the Bessemer Gold Medal of the Iron and Steel Institute in 1877, and, in 1889, the Prince of Wales, on the recommendation of the Council, awarded him the Albert Medal of the Society of Arts.

IV.

THE ALLOYS RESEARCH REPORTS.[1]

The Alloys Research Committee—First Report—Second Report—Third Report—Fourth Report—Fifth Report—General Index to the Reports and Discussions.

In the early part of 1890, Roberts-Austen was afforded an opportunity of commencing a series of researches in extension of work which had already occupied his attention for many years. This was brought about by the foresight and generosity of the Institution of Mechanical Engineers.

On the recommendation of the late Dr. Anderson, then Director-General of Ordnance Factories at Woolwich and a Vice-President of the Institution, the Council decided to appoint a research committee to be called the Alloys Research Committee, with the object of furthering the investigations which Roberts-Austen had already made into the effects of small admixtures of impurities on the mechanical properties of metals.

During the ten years which followed, five reports were presented to the Institution. A general index to all the subject-matter contained in them is appended, and it is hoped that, at some future time, the Reports may be re-published as a whole.

It was, perhaps, through the medium of these Reports and the vigorous discussions which they provoked that Roberts-Austen's influence had the greatest practical effect and led to the most wide-spread and permanent results.

At the time when men occupying the highest positions in the engineering world were frankly sceptical as to the possibility of the pyrometer or the microscope serving any useful purpose at all as an indication of the suitability or otherwise of steel for engineering purposes, Roberts-Austen aroused interest by his enthusiasm and carried conviction by his demonstrations.

Although much of the work contained in the Reports is now accepted as common knowledge and consequently appears to the present generation as commonplace, yet it is instructive to reflect how new it appeared twenty years ago.

The very discursiveness of the earlier reports provoked an amount of discussion from all sources which in no small measure contributed to make the work known and appreciated. The immediate result was to cause emulation among men dealing with metallurgical problems which differed very widely in their nature. In fact, one of the greatest features of Roberts-Austen's usefulness was the close touch which he kept with men who were working in divers places and ways and from whom came the knowledge of problems and phases of problems which could never have reached a man occupied in the comparative seclusion of an ordinary laboratory. Metallurgically speaking, he knew everyone and he was readily accessible to all.

This intercourse added daily and almost hourly to his already restless and at times feverish enthusiasm. Scarcely a day passed without a visit

[1] Copies of the Alloys Research Reports may still be obtained from the Secretary of the Institution of Mechanical Engineers, Storey's Gate, S.W.

to the Mint by some worker, either eminent himself already or seeking instruction or enlightenment on some aspects of the work. To these visitors every facility was freely offered. Often the day was entirely taken up by such visits, the researches being continued at night.

It was in this way that Roberts-Austen upheld the best traditions of metallurgical research in this country at a time when rapid advance was being made in all directions, and in doing so he won the esteem and in many cases the close affection of his fellow-workers in other countries.

It was, perhaps, with the publication of the Fifth Report, devoted entirely to the consideration of the changes in steel produced by thermal treatment and the changes in micro-structure which accompany them, that the greatest interest was aroused.

Enquiries and suggestions poured in from all quarters and consultations were held daily. The apparatus, which would now be regarded as somewhat crude, was made the model from which more elaborate plant was installed all over the country.

The excellence of the photographs published in this Report bear testimony to the patience and care which were devoted to the work in these early days. Taken under extremely difficult and trying conditions they were selected from among large numbers of negatives which had to be rejected.

Those who know the care with which Roberts-Austen weighed and considered every statement he made and the illustrations he used to support his statements can alone realise the amount of work which is represented by matter which may appear meagre in print or which is represented by solitary photographs in an appendix. As a consequence of this, although much of his work has been subsequently amplified, but little has been rejected as inaccurate or hasty, while striking instances have occurred of complete corroboration of his results by recent workers on points which have been in doubt for many years.

The development of the solution theory of the condition of carbon in iron which followed the publication of the Fifth Report and the application by Roozeboom of the Phase Law of Gibbs to Roberts-Austen's results will make it historic in the progress of the metallurgy of iron and steel.

In reviewing the work of these Reports in somewhat closer detail it is not intended that any attempt should be made to form a criticism of them. That should come more appropriately from other sources and from those whose duty it is to teach to others the principles with which Roberts-Austen grappled so long and so earnestly.

He clearly understood that useful results are only achieved by beginning somewhere and doing things. In this way he revealed to himself unsuspected aspects of the problems he was engaged upon. Much of Roberts-Austen's earlier work was in this sense a groping for principles which by their elusiveness led him to other and wider fields. In these fields he put in his "section posts," leaving to others the work of surveying the land more completely.

This work has been faithfully continued by many who came either directly or indirectly under his influence. Apart from the National Physical Laboratory to which the work of the Alloys Research Committee was transferred at his death, one may point to the youthful, but vigorous, Institute of Metals as definitely carrying on the work which he had so much at heart.

The circumstances which gave rise to the Alloys Research Committee

are set forth in the Proceedings of the Institution of Mechanical Engineers (*Annual Report*, January 29, 1890, p. 6).

"On the recommendation of Dr. Anderson, arising out of Prof. Roberts-Austen's investigations into the application of the periodic law to the mechanical properties of materials, the council have recently decided upon starting a research committee with the object of investigating the effects of small admixtures of certain elements on the mechanical and physical properties of iron, copper, and lead. This committee, of which Dr. Anderson has been appointed Chairman is to be called the 'Alloys Research Committee.'

"They are led to believe that by dealing in the first instance with these three distinct metals simultaneously the investigations into their properties when alloyed with minute doses of foreign ingredients may mutually throw light upon one another, and thereby facilitate the progress of the research and the attainment of results having a practical bearing upon the work of mechanical engineers.

"On a former occasion the council received from Mr. John A. F. Aspinall the valuable suggestion of the desirability of enquiring into the serious deterioration experienced during recent years in the durability of the copper fire-boxes and brass tubes of locomotive boilers; and it seems not unreasonable to hope that one result of the investigations now about to be entered upon may be to elucidate the true causes of this deterioration and to indicate the means of restoring to copper the identical properties which enabled locomotive fire-boxes of this material to accomplish formerly so much longer a mileage than it has latterly been found possible to get out of them.

"The laws regulating the effects of small admixtures of other elements with iron will also, it is hoped, be arrived at. These are some of the instances of many similar benefits which may be looked for from the work of the newly started research committee."

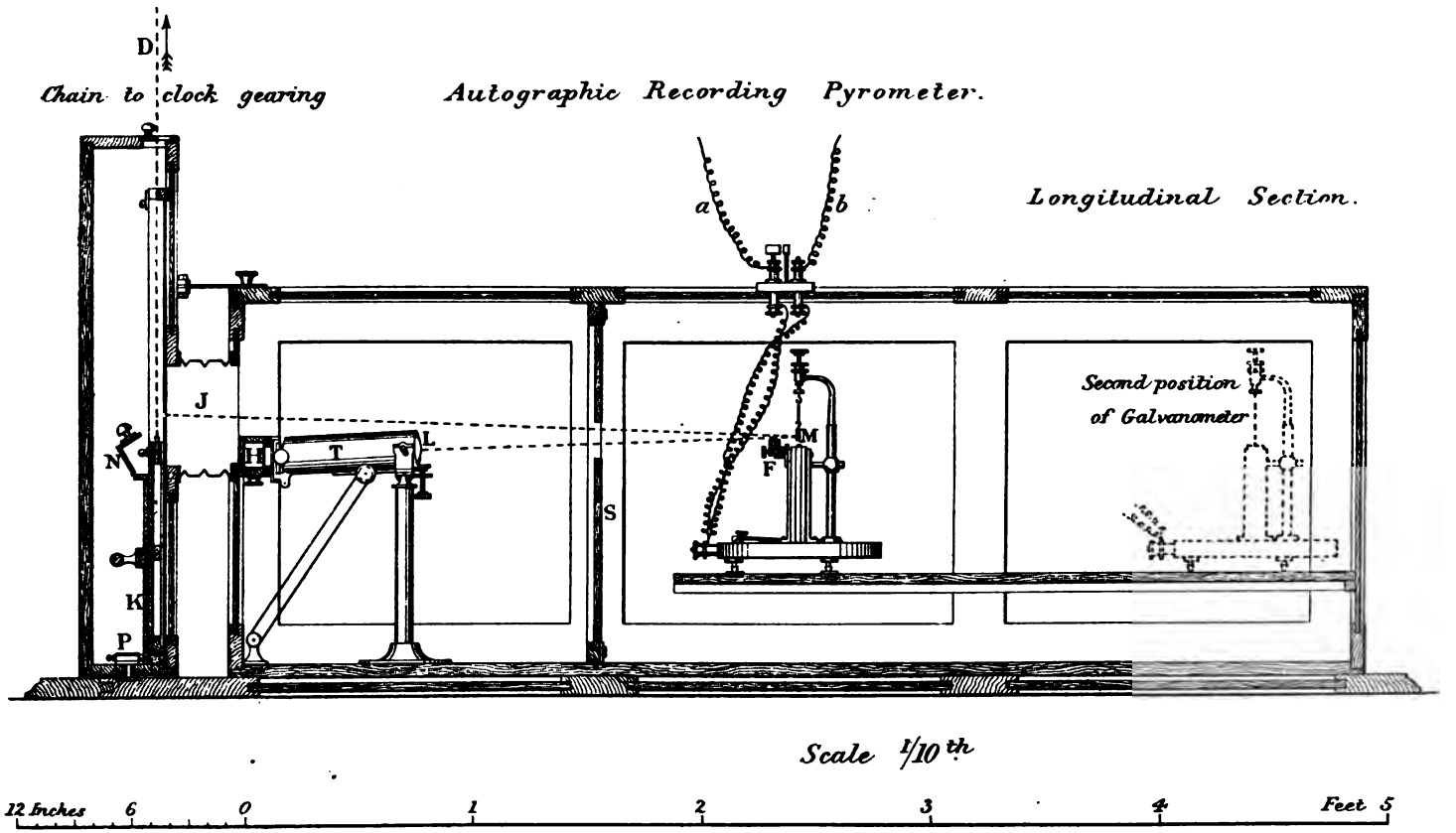
The First Report.—The First Report of the Committee was presented in October, 1891, and the nature of the work which had been undertaken was set out in the opening paragraph :—

"At the request of the Alloys Research Committee I began, in April, 1890, to investigate the effects of small admixtures of certain elements on the mechanical and physical properties of iron, copper, and lead. The Committee desired me to extend an investigation I had previously made upon the application of the 'periodic law' of Newlands and Mendeléeff to the mechanical properties of metals. This law, as originally expressed, states that 'the properties of the elements are a periodic function of their atomic weights.' It has already been shown that the effect of impurities added to gold is nearly proportional to their atomic volumes, the larger the volume of the atom the greater being its effect (*Phil. Trans. Roy. Soc.*, vol. clxxix., 1888, p. 339); and it became interesting to determine whether this holds good for other metals."

The result of Osmond's work on the allotropy of iron and of his experimental study of the action of impurities on iron were then discussed.

Considerable space was next devoted to the question of pyrometry which formed an important feature at that time of the work of the Committee.

A fundamental necessity in carrying out the investigations was a trust-



2nd Alloys Research Report
(from *Proc. Inst. Mech. Eng.*, 1893).

worthy pyrometer which would measure higher temperatures than had been possible up to that time.

This was found in the adaptation by Roberts-Austen of the Le Chatelier pyrometer to give autographic records. A careful description was given of the apparatus employed and of the means adopted to obtain photographic records of the heating and cooling of masses of metal.

Following this descriptive work comes an account of the application of this instrument to the examination of the liquation of the alloys of silver and copper and also of the cooling of masses of steel.

In fulfilment of the original purpose of the Research Committee to study the influence of small quantities of impurities, much time and work were devoted to studying the effect of such impurities in lowering the freezing point of gold—a metal which offered special advantages for investigations of this nature, as it may be prepared in a very high degree of purity, and is not liable to contamination by oxidation. Moreover, much was already known of its mechanical and thermal properties as influenced by small quantities of impurities.

The "atomic fall" of the freezing point of gold was determined when the added impurity was lead, bismuth, platinum, silicon, manganese, aluminium, and silver respectively.

The Report then records an account of experiments in connection with steel which will be seen to have a very important bearing on subsequent work and on the present practice in all steel works. A portion of this part of the Report may be quoted (p. 564).

"From the engineer's point of view the most interesting information which the pyrometer has as yet afforded is connected with the measurement of internal stresses in iron and steel. Osmond's work has shown that molecular changes take place in steel; and it is evident that the occurrence of these changes must be of vital importance when the metal is subjected at high temperatures to mechanical operations such as rolling and forging. The question naturally arises, do the molecular changes in the iron take place at one moment throughout the mass of metal? That is, is the rate of cooling approximately uniform throughout the mass? Or does the external portion of a hot ingot cool so much more rapidly than the centre as to allow the molecular changes in the iron, and the alterations in the relation between the carbon and the iron, to become completed near the surface long before they take place in the interior of the mass? The experimental difficulties in the way of obtaining information upon these points have hitherto appeared to be insuperable; but the pyrometric method used in this research affords most important evidence."

Experiments were then described and curves were given showing that the molecular changes at the centre and at the circumference of the same ingot take place at different times and at different temperatures.

The importance of this was at once recognised, as Osmond had already pointed out that the rate of cooling has a measurable effect upon the temperatures at which molecular changes occur.

The Report concludes with the following paragraph:—

"In all these experiments it was found that the flow of heat from the centre of such an ingot was not sufficiently rapid to prevent there being considerable variations in temperature within the mass. There can be but

little question that such experiments well deserve careful attention, and in the hands of competent observers should be fruitful of results."

Second Report.—In presenting the Second Report reference was again made to the Periodic Law of Newlands and Mendeléeff upon which a large portion of the work described in the First Report had been based. Attention was directed to some further considerations which seemed to point to the possibility that the influence of small quantities of added elements on the mechanical properties of masses of metal will be in proportion to the atomic volume of the impurity. In the first place, it was pointed out that the researches of Raoult and the conclusions of Van't Hoff and Arrhenius led to the view that the molecules of small quantities of elements distributed through a mass of a solvent retain their individuality; that is, they remain free and do not enter into combination with the mass. Further, as regards metals, the work of Heycock and Neville, as well as the results of experiments described in the previous Report, pointed to the conclusion that the added elements may retain their freedom when they are present in much larger quantities than 0·2 per cent., which was the amount of added matter which had been usually dealt with throughout the Committee's researches. The point as to whether the added element does or does not remain free in the mass of the solvent was shown to be a vital one in limiting the scope of the enquiry.

This question was carefully analysed and it was recognised that an attempt to prove the nature of the influence of atomic volumes merely by mechanical tests would certainly lead to anomalies and more or less grave irregularities being encountered.

Investigation was not, however, limited to mechanical tests, independently of which it had been shown that the influence of impurity on the molecular transformations in iron, studied by Osmond, might be demonstrated in several ways. These transformations might be assisted by the presence of impurity, the temperature at which they occurred might be altered or the molecular changes might even be entirely prevented by the presence of elements which behave in strict accordance with the law of atomic volumes.

Having regard to the importance to molecular physics of the view put forward should it prove to be a correct one, the evidence of other observers was considered as bearing on the question. Tomlinson had shown that the thermal capacity of metals closely follows their atomic volumes, while as regards their elasticity he had given a table showing the relation of Young's modulus to the atomic volumes. Sutherland had shown that the rigidity of metals also bears a close relation to these volumes. Other evidence supporting the view had been furnished by Fessenden and by M. J. Werth.

The next question dealt with in the Report was that of molecular porosity. A consideration of this had arisen from the remarkable series of experiments which had been recently made by Warburg and Tegetmeier. These experiments had demonstrated the possibility of producing a degree of porosity in vitreous bodies which would admit the passage of elements having comparatively small atomic volumes, while other elements having larger atomic volumes were strained off, thus occasioning a mechanical sifting of the elements. The results of these experiments, therefore, afforded additional evidence of a direct connection between the properties of a mass and the volume of its atoms. This portion of the Report concludes with the words—

"In all probability, therefore, the introduction of free molecules of an added element must create a disturbance, the nature and magnitude of which will bear some relation to the volume of the disturbing atom."

At this point the Report passes to the consideration of work which had been conducted essentially from the engineer's point of view, prominence being given to mechanical tests, since it is upon these that the employment of materials depends. The question was raised whether normal copper can be made to assume an allotropic state analogous to that in which there was reason to believe that iron can exist. The effect of mechanical and thermal treatment upon copper was then considered and figures were given showing how different may be the properties of a metal even when chemically pure.

Exhaustive experiments were made on the influence of impurities on copper and the results were tabulated at some length. The elements selected for the study of this question were arsenic, antimony, and bismuth, and this section of the Report constituted one of great importance to engineers. Special interest attaches to the experiments on the influence of bismuth on copper in the discovery of a low subordinate freezing point which was recognised as the determining cause which enables the metal to assume a highly crystalline and intensely brittle structure. This could not have been revealed by any other method but those which had been adopted in carrying out the work of the committee, and at that time it afforded a striking example of the possibilities of usefulness ahead.

The portion of the work bearing directly upon the use of copper plates in the fire-boxes of locomotives was considerably amplified by the results of tests and analyses published in conjunction with the Report by Mr. William Dean who was at that time the Locomotive Superintendent of the Great Western Railway.

The effects of pressure on metals was next considered. It was pointed out that the passage of iron from one allotropic modification to another is accompanied not only by a change of heat capacity, but also by a change of volume. The matter had been referred to in the previous Report, but particulars were now given of further experiments carried out by compressing steel in a hydraulic press in order to obtain recalescence at a lower temperature than would otherwise be the case. Other experiments were made with the triple alloy of bismuth, lead, and tin, known as Newton's metal. This alloy shows a remarkable rise in temperature long after the metallic mass has solidified. Certain analogies were shown to exist between the behaviour of this alloy when suddenly cooled and the changes which take place in steel during hardening. Carefully devised experiments were made to enable the effect of pressure on this metal during cooling to be studied.

Chromium steel was examined from the point of view of the shifting of the temperature at which the molecular changes in iron and steel take place, and attention was drawn to the importance of studying the relation of this metal (chromium) to carbon and to iron.

Further details were given of the method of making autographic pyrometric records, and the Report concludes with a general summary and discussion of the points which had been raised.

Third Report.—In the Second Report attention had been directed to the experiments of Warburg and Tegetmeier on molecular porosity. Considerable interest had been taken in the results of these experiments and they

were regarded as of sufficient importance to warrant repetition. The first portion of this Report deals, therefore, with the confirmation and extension of these experiments which, however, were only considered as incidental to the main investigation of the Committee. The general conclusion following from this work in which it was shown that molecular porosity could, in a sense, be gauged and the mechanical influence of the volume of the atom made evident, was the direct connection which was revealed between the properties of a mass and the volume of its atoms.

Much of the work which follows this is in the nature of exploratory research in various directions. Curves were given and described showing the cooling of electro-iron, of standard gold containing bismuth as an impurity, of aluminium-copper alloys, and of iron-aluminium alloys. With regard to the latter, observations were made of their spontaneous disintegration, a phenomenon which has since received much attention in connection with aluminium alloys.

Experiments were next described which had been carried out in conjunction with Sir Thomas Wrightson with the object of ascertaining whether the welding of iron is attended with a fall of temperature, as is the case in the regelation of ice. The welding was conducted by electrical methods and pyrometric measurements were made during the application of pressure to the plastic iron and the analogy to regelation of ice was established.

In the latter part of the Report, the relation of the small amount of impurity to the mass of the metal in which it is contained is again discussed, and also the relations between the melting points of metals and their tenacity and the Periodic Law of Mendeléeff. It was pointed out that the absolute temperature of the melting point of a metal must be closely connected with its atomic volume, since the former is inversely proportional to the rate at which the amplitude of the oscillations of the molecules increases with temperature; and the rate of increase of amplitude at any given temperature is obtained by multiplying the ordinary thermal coefficient of linear expansion by the cube root of the atomic volume.

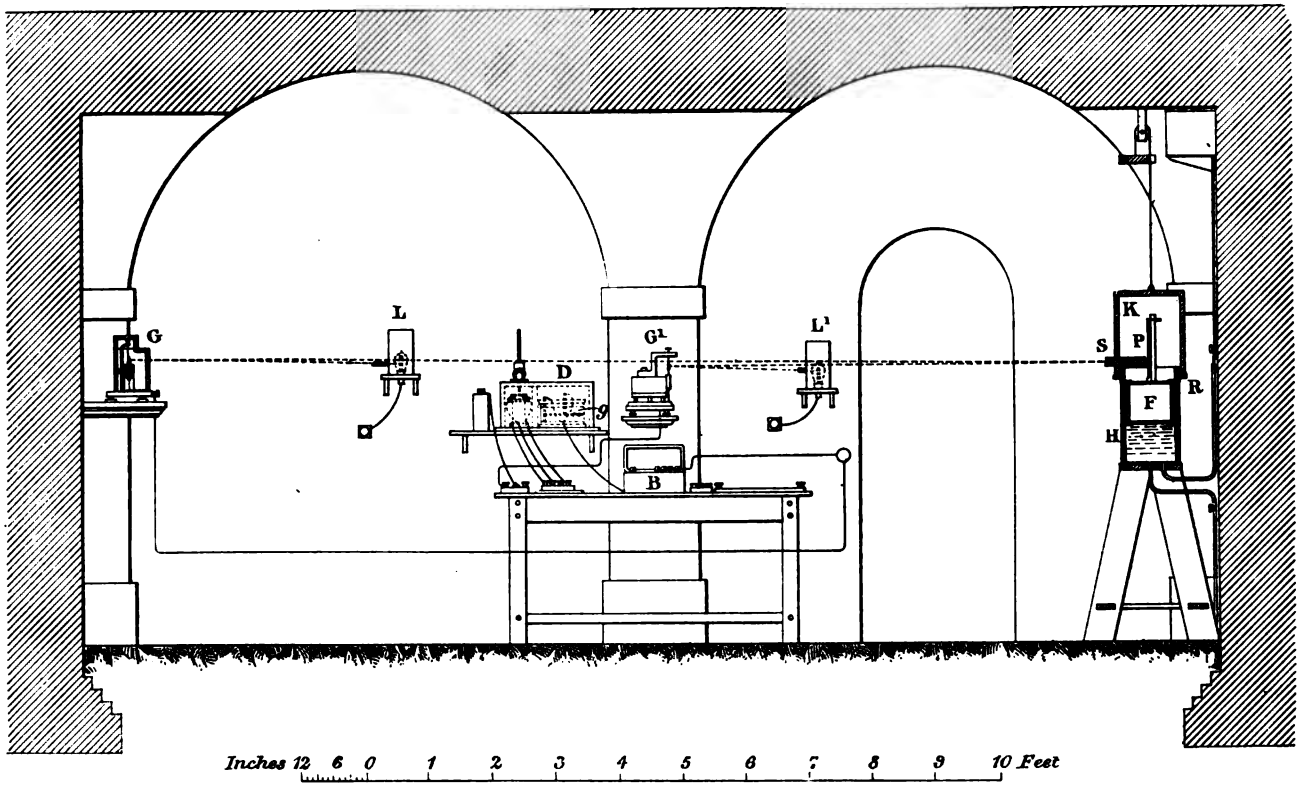
The work of Dewar and Fleming on the behaviour of metals at very low temperatures, then but recently published, was shown to have a direct bearing on this question and the results of their investigations were discussed.

Two appendices were printed with this Report embodying researches by two of his students—Mr. Alfred Stansfield[1] and Mr. Allan Gibb. The titles of their work were respectively the "Pyrometric Examination of the Alloys of Copper and Tin" and the "Elimination of Impurities during the Process of making 'Best Selected' Copper."

With regard to the work of Mr. Stansfield, who was then assisting Roberts-Austen in the work of the Alloys Research Committee, its importance can hardly be over-estimated. Not only does it represent the first attempt to give an explanation of the copper-tin series of alloys as a whole, but it also marks the beginning of all the investigations which have since been made in correlating the physical and mechanical properties of alloys with their freezing-point curves.

Fourth Report.—This Report deals first with some general considerations respecting the position of the research at this time; secondly, with the copper-zinc series of alloys or brasses; and thirdly, with certain relations between

[1] Now Professor of Metallurgy at the M'Gill University, Montreal.



General Arrangement of the Recording Apparatus at the Royal Mint (for differential work).

5th Alloys Research Report
(from *Proc. Inst. Mech. Eng.*, 1899).

the fusibility and strength of alloys which involve considerations as to the constitution of alloys generally. An account is also given of investigations of the molecular mobility of solid and molten metals as measured by their relative rates of diffusion. A description is also given of the means taken to render the calibration of the pyrometer more accurate by direct comparison with the air thermometer.

The opening paragraphs of the Report contain much which is of considerable historical interest, and they constitute, moreover, a concise statement of the position at which the research had arrived. It has been thought desirable to reproduce them in full.

"The value of the experiments on the nature and properties of alloys, which were originated by the Institution of Mechanical Engineers in 1890, has received wide and appreciative recognition in this country and abroad. It may fairly be claimed that they have stimulated similar work in France in a remarkable way; for the constitution of our Alloys Research Committee, and the course they have adopted, have confessedly been closely followed by the 'Commission des Alliages' of the Société d'Encouragement. The names of some of the best known scientific workers in France are included in the list of this Commission; and what is justly called a 'vast programme of research' has been entrusted to six experimenters whose individual reputations are already well established. The Institution of Mechanical Engineers has conducted the researches on alloys entirely at its own cost; but in France the 'necessary resources for the realisation of the experiments' have been furnished in part by the Société d'Encouragement, and in part by individuals and public companies. The list of these includes M. Solvay, la Société Royale Asturienne, six of the great railway companies of France, la Société des Forges et Aciéries de la Marine, la Société de Chatillon et Commentry, and la Société Française des Métaux. The first report of this Commission has been published during the present year, and reference will subsequently be made to it. The Institution of Mechanical Engineers, however, has not only influenced indirectly the advance of scientific knowledge by stimulating research in other countries; it has done much to sustain the reputation of our own country, by affording means for conducting experiments, the results of which have a scientific as well as an industrial application. The necessity for keeping pace with such research work as is being done in Germany has been strenuously urged in letters published in *The Times* during the months of August and September last; and it does not seem to be recognised how much good work, of the kind advocated, has already been accomplished by this Institution. It should not be forgotten, moreover, that excellent investigations on alloys have also recently been made at Cambridge by Heycock and Neville, whose work has been carried on side by side with that of our Committee.

"How much influence the Institution of Mechanical Engineers is exerting, in connection with what has been justly called the 'renaissance of inorganic and physical chemistry,' may be gathered by comparing this series of Reports with some recent observations of Dr. Étard of the École Polytechnique. He has pointed out [1] that 'one prominent fact stands out more and more in the researches in later years, and its manifestations deserve to be collected,

[1] *Revue des Sciences pures et appliquées*, September, 1896, p. 755.

space is devoted to an exposition of the meaning and significance of eutectic alloys and also of melting and freezing points—matters which, for lack of clear definition, had hitherto caused some confusion.

With the actual results of the work on the brasses, it is not proposed to deal here, but it should be clearly indicated how very carefully this work was done and how completely all the fundamental facts in connection with these alloys were defined. Subsequent workers have devoted much time and labour to further elucidating the behaviour of the alloys of this remarkable series, but a reference to the original work described in this Report will show how far was the advance made at this time towards a conception of the series as a whole.

A brief consideration was next given to the relations between the fusibility and strength of alloys of two constituents when influenced by the intervention of a third constituent in small quantities. The particular cases described were those alloys of copper and zinc to which iron is added (known as Sterro and Aich's metal). An analogy was drawn between the behaviour of these alloys and the segregation observed in an ingot of base bullion containing small proportions of zinc.

Following this some general observations are made on the investigation of alloys which conclude with some very pertinent remarks on the difficulties connected with the study of the effect of small quantities of impurities—remarks which, had they been fully grasped by subsequent workers, might have resulted in much labour being more profitably directed. The Report says :—

"For instance, assuming that copper of a high degree of purity, as indicated by chemical analysis, gives certain constants—limit of elasticity, modulus of elasticity, tensile strength, and reduction of sectional area—it might at first appear that nothing could be simpler than to test the mechanical properties of the same copper, to which, say, $\frac{1}{10}$ of 1 per cent. of lead has been added. But the question at once arises, what has happened to the metallic lead ? Has it remained free ? Has it united with a certain amount of the copper to form a fusible eutectic alloy ? Has it abstracted oxygen from the copper, becoming itself oxidised ? Has it united with the copper to form a 'solid solution' ? Or lastly, does it form a true chemical compound with the copper ? It is only reasonable to ascertain what has probably happened to an added element, before making elaborate tests on a metal in which chemical analysis shows only that a certain amount of the foreign element is present, but is incompetent to disclose the condition in which it exists in the metal."

The diffusion of metals, which had recently formed the subject of a Bakerian Lecture to the Royal Society, was discussed in relation to alloys generally and with regard to the diffusion of solid metals in each other, it was pointed out that the experiments had led to the recognition of the fact that it is possible actually to observe and measure the migration of the constituent atoms in a metal or alloy at the ordinary temperatures, pointing to unexpected possibilities of structural changes in metals used in engineering construction generally.

In continuance of the work described in previous reports on the relation between melting points of alloys and the atomic volumes of their constituents, some additional experiments were described.

The Report concludes with an account of further improvements which

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had been effected in the recording pyrometer and of comparisons of the thermo-junction with the air-thermometer.

Thus, it will be seen that the range covered by the work of the Committee had been largely diversified and evidence had been gathered of constant and active molecular movement in solids.

An important announcement was made by Roberts-Austen in the course of the discussion with regard to the analogy between the alloys of the carbon-iron series (steel and cast iron) and ordinary saline solutions. Later in the same discussion the question was further developed by Dr. Stansfield, his assistant at this time. A closer study of this analogy formed the subject of the next Report.

The Fifth Report.—The ultimate transference of the work of the Alloys Research Committee to the National Physical Laboratory was foreshadowed in the opening paragraph of the Report. It was pointed out that the Committee had exerted a noteworthy influence in connection with the preliminary enquiry which had led to the recommendation that a National Physical Laboratory should be established, having its control vested in the Royal Society. The research work, therefore, on which the Committee had been so long engaged, was fully and officially recognised, not only as having rendered important services to industry, but also as being of national importance.

The results published in the Fifth Report, which are of outstanding importance and of far-reaching significance, are those which sought to support the view that carburised iron should be considered as a solution and brought into line with ordinary solutions. The series of Reports, as a whole, had abundantly shown that alloys behave like saline solutions, and it was recognised that a point of the utmost metallurgical importance would be gained if it could be shown that steel and cast iron may be regarded in the same way.

In the course of the Fourth Report, curves had been shown which clearly indicated the possibility of such an explanation of carburised iron, while the provision of a new and highly sensitive method of recording temperature changes—described at some length—made it possible to resume that part of the investigation. Although such curves had been obtained previously and quite independently in France by M. Osmond, so long before as 1888, and more recently by M. Henri Le Chatelier, and in this country by Roberts-Austen himself, those published with the Fourth Report constituted the first attempt to embody in curves a comprehensive series of results. Following the issue of that Report the importance and urgency of the work became more and more evident.

Before proceeding to the examination of the series of carbon-iron alloys the remarkable capabilities of the delicate methods of pyrometric record now available were demonstrated by reference to a special case furnished by the cooling of electro-iron from a white heat. The publication of the complete curve showing the temperature changes in pure carbon-free iron afforded striking evidence of the soundness of the views which had been adopted as to the allotropy of iron (see Plate X). The significance of each molecular change as indicated by the evolutions of heat during the cooling of this pure iron was discussed at some length. In addition to verifying those molecular changes which were already well known, the investigation placed the relation of iron and hydrogen in a new light.

Carbon-iron Solutions.—Curves were now presented to the Institution which represented the constitution of carburised iron as far as it was known at that time. These curves were built up from the results of a long series of investigations which had been conducted on a series of carbon-iron alloys specially prepared with a progressive variation of carbon, but with the amounts of the other elements maintained practically constant or at any rate varying in a definite way. These constitute the well-known curves which have been the basis of all subsequent work, both theoretical and practical. From them Roozeboom drew his conclusions as to the applicability of the Phase Law of Gibbs to the consideration of carburised iron (Plate XI.).

The latter part of the Report is devoted almost entirely to a description of the methods and a discussion of the possibilities afforded by the microscope. At the time of its publication the greatest attention was directed, perhaps, to this portion of the work and to the photographs which were reproduced. The inaccessibility of information and experience in this branch of metallurgical research at that time gave this portion of the Report the value of a text-book to those who were anxious to take up the work.

Reference should be made to the generous appreciation, which was expressed at the conclusion of each Report, of the services rendered to him by his assistants during the conduct of tedious experiments extending over so many years.

His indebtedness was freely acknowledged to those Associates of the Royal School of Mines who had assisted him at the Mint in carrying out these researches. To Henry C. Jenkins (1st and 2nd Reports), who was afterwards Government Metallurgist of Victoria; to Alfred Stansfield (3rd, 4th, and 5th Reports), Professor of Metallurgy at the M'Gill University, Montreal, since 1901; to William H. Merrett (4th and 5th Reports), Assistant Professor of Metallurgy at the Royal School of Mines; and to A. J. Brett (5th Report), now Manager of the Crown Mines, Johannesburg.

THE SIXTH REPORT.

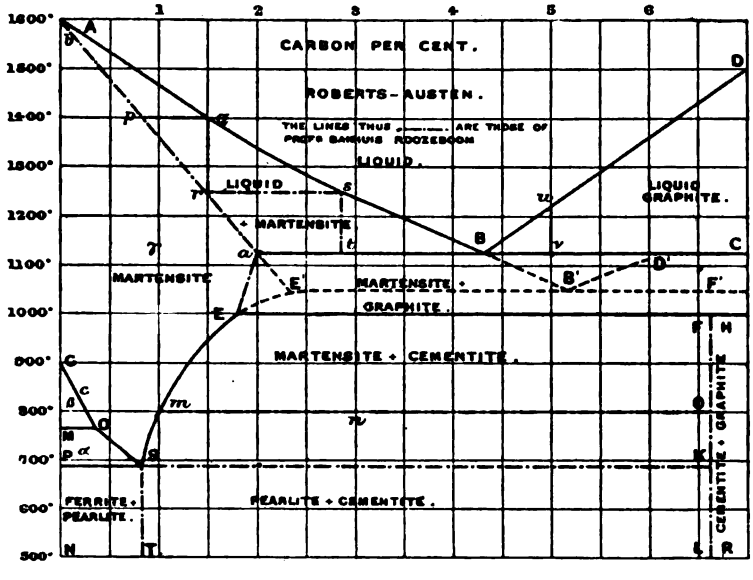
At the time of Roberts-Austen's death a large amount of experimental work had been carried out by Mr. (now Professor) W. H. Merrett in connection with the preparation of a Sixth Report, the subject of which was to be the Heat Treatment of Steel.

Professor William Gowland, Roberts-Austen's friend and successor at the Royal School of Mines, readily undertook the task of completing this work.

The Report was presented to the Institution of Mechanical Engineers by Professor Gowland in January, 1904—two years after Roberts-Austen's death—and in doing so he paid generous tribute to the work of Mr. Merrett in carrying out the researches.

The work of the Alloys Research Committee was subsequently handed over to a Special Department of the National Physical Laboratory, where it has been continued.

In concluding this attempt to give some account of the work which was embodied in these Reports, great regret is felt that owing to the descriptive nature of much of the matter contained in them, and the large number of plates and photographs by which they were accompanied, it is quite impossible to reproduce them more fully in this volume, and so to do full justice to the immense amount of work which they represent, and to the importance of the place which they fill in the history of the study of alloys.



Freezing-point Curves of the Carbon-Iron Series.

GENERAL INDEX TO THE ALLOYS RESEARCH REPORTS.

From the Index to the Proceedings of the Institution of Mechanical Engineers, 1885-1900.

Second Report by W. C. Roberts-Austen, 1893, 102.

Fourth Report by W. C. Roberts-Austen, 1897, 31.

Discussion.

V.

IRON AND STEEL.

On the Hardening and Tempering of Steel—Iron and Steel in the Nineteenth Century (Presidential Addresses to the Iron and Steel Institute)—Metallurgy in its Relations to Engineering (James Forrest Lecture)—Steel Rails—Explosives and Ordnance—Experiments on the Hardening and Tempering of Steel—Steel for the Manufacture of Dies—Electro-deposition of Iron—Carburisation of Iron by the Diamond—Rate of Diffusion of Carbon in Iron—Bibliography.

ON THE HARDENING AND TEMPERING OF STEEL.[1]

A Lecture delivered on September 13, 1889, *by Roberts-Austen before the Members of the British Association.*

"And if any man think that I make too great a wonder of it, as I know there be many (never born to be Philosophers) who can hardly be brought to admire anything that is known and ordinary: I could appeal to many both ancient and late, men of great reputation and learning . . . who have given it place among the greatest miracles of the world."

—*Meric Casaubon*, 1655.

THE fact that the British Association meets this year at Newcastle no doubt suggested to the Council that it would be well to provide, for the first time since 1848, a lecture on a metallurgical subject. In that year a discourse was delivered at Swansea by Dr. Percy, one of the most learned metallurgists of our time, who has recently passed away, after having almost created an English literature of metallurgy by the publication of his well-known treatises, without which it would have been comparatively barren. It was to him that the country turned in 1851 when it became evident that our metallurgists must receive scientific training.

I know that it has occurred to many that the various problems involved in the "hardening and tempering of steel" must be incapable of adequate treatment in the brief limits of a discourse like this, while others will think that the details of the process, which is practised daily in thousands of workshops, are so well known that it is unnecessary to devote a lecture to the subject. It seemed to me that the entire question was the most important I could choose, partly because it will enable a large number of people who are engaged in industrial work, and who are not expected to think about it in a scientific way, to know how such facts as we shall have to examine have been dealt with by scientific investigators; while those of our

[1] *Nature*, Nov. 7 and 14, 1889.

members who do not consider that their thoughts or work are scientific in its strictest sense, may perhaps be interested to see how absolutely industrial progress depends upon the advancement of science. This consideration has led me to deal with the subject in a somewhat comprehensive way. The treatment of iron in its several forms is the thing that we as a nation do well. If it be true that national virtues are manifestly expressed in the industrial art of a people, we may recall the sentence in Mr. Ruskin's "Crown of Wild Olive," in which he says, "You have at present in England only one art of any consequence—that is, iron-working," adding, with reference to the manufacture of armour-plate, "Do you think, on those iron plates your courage and endurance are not written for ever, not merely with an iron pen, but on iron parchment?" It may be well, therefore, to consider what properties iron possesses which entitle its application to industrial use to specially represent the skill and patience of the nation.

In 1863, Lord Armstrong, in his address as President of this Association, expressed the hope "that when the time again comes round to receive the British Association in this town, its members will find the interval to have been as fruitful as the corresponding period," since the previous meeting in 1838, "on which they were then looking back." In one way at least this hope has been realised, for the efforts of the last twenty years have resulted in the development of an "age of steel." When the Association last met here, steel was still an expensive material, although Bessemer had, seven years before, communicated his great invention to the world through the British Association at its Cheltenham meeting. The great future in store for Siemens's regenerative furnace, which plays so important a part in the manufacture of steel, was confidently predicted in his Presidential address by Lord Armstrong, than whom no one was better able to judge, for no one had done more to develop the use of steel of all kinds.

Steel, we shall see, is modified iron. The name iron is in fact a comprehensive one, for the mechanical behaviour of the metal is so singularly changed by influences acting from within and without its mass, as to lead many to think, with Paracelsus, that iron and steel must be two distinct metals, their properties being so different. Pure iron may be prepared in a form as pliable and soft as copper, steel can readily be made sufficiently hard to cut glass, and notwithstanding this extraordinary variance in the physical properties of iron and certain kinds of steel, the chemical difference between them is comparatively very small, and would hardly secure attention if it were not for the importance of the results to which it gives rise. We have to consider the nature of the transformations which iron can sustain, and to see how it differs from steel, of which an old writer has said,[1] "Its most useful and advantageous property is that of becoming extremely hard when ignited and plunged into cold water, the hardness produced being greater in proportion as the steel is hotter and the water colder. The colours which appear on the surface of steel slowly heated direct the artist in *tempering* or reducing the hardness of steel to any determinate standard." There is still so much confusion between the words "temper," "tempering," and "hardening," in the writings of even very eminent authorities, that it is well to keep these old definitions carefully in mind. I shall employ the word

[1] "The First Principles of Chemistry," by W. Nicholson, p. 312 (London, 1790).

tempering in the sense of softening, as Falstaff uses it when he says of Shallow :—

"I have him already tempering between my finger and my thumb, and shortly will I seal with him." [1]

Softening, that is, as brittle wax does by the application of gentle heat. *Hardening*, then, is the result of rapidly cooling a strongly heated mass of steel. *Tempering* consists in reheating the hardened steel to a temperature far short of that to which it was raised before hardening: this heating may or may not be followed by rapid cooling. *Annealing* consists in heating the mass to a temperature higher than that used for tempering, and allowing it to cool slowly.

First, let the prominent facts be demonstrated experimentally.

[Three sword-blades of identical quality, made by an eminent swordsmith, Mr. Wilkinson, were taken. It was shown by bending one that it was soft; this was heated to redness and plunged into cold water, when it became so hard that it broke on the attempt to bend it. Another was bent into a bow, the arc of which was four inches shorter than the sword itself, a common test for "temper," and it sprang back to a straight line when the bending force was removed; this had been tempered. A third, which had been softened by being cooled slowly, bent easily and remained distorted.]

The metal has been singularly altered in its properties by comparatively simple treatment, and all these changes it must be remembered have been produced in a solid metal to which nothing has been added, and from which nothing material has been taken. The theory of this operation which I have just conducted has been laboriously built up, and its consideration introduces many questions of great interest both in the history of science, and in our knowledge of molecular physics. First as regards the history of the subject. The knowledge that steel might be hardened must have come to us from remote antiquity. Copper hardened with tin was its only predecessor, and it continued to be used very long after it was known that steel might be hardened. It would, moreover, appear that a desire to appreciate the difficulties of a people to whom cutting instruments of hard steel were unknown, seems to have induced experimenters in quite recent times to fashion implements of bronze, and a trustworthy authority tells us that "Sir Francis Chantry formed an alloy containing about 16 parts of copper, 2½ of zinc, and 2½ of tin, of which he had a razor made, and I believe even shaved with it." [2] The Greek alchemical manuscripts which have been so carefully examined by M. Berthelot give various recipes from which it is evident that in the early days the nature of the quenching fluid was considered to be all-important. There were certain rivers the waters of which were supposed to be specially efficacious. Pliny, who says that the difference between waters of various rivers can be recognised by workers in steel, also knew that oil might be used with advantage for hardening certain varieties of the metal. It is sad to think how many of the old recipes for hardening and tempering have been lost. What would we not give, for instance, for the records of the Gallic prototype of our Iron and Steel Institute, the

[1] King Henry IV., Part II., Act iv., Scene 3.

[2] "Engines of War," by H. Wilkinson, p. 194 (1841).

"*Collegium Fabrorum Ferrariorum*,"[1] a guild with similar aims, formed in the time of the Roman Republic, for the advancement of knowledge, for the good of the State, and not for that of its individual members? Theophilus,[2] priest and monk, writing in the eleventh century, gives very quaint instructions in the art of hardening steel; the belief, however, in the efficacy of curious nostrums and solutions could hardly have been firmer at any period than in the sixteenth century. Shakespeare suggests that Othello's sword "of Spain" had been hardened in a cold stream, for he says it had

"the ice brook's temper";

but cold water was far too simple a material for many a sixteenth century artificer to employ, as is shown by the quaint recipes contained in one of the earliest books of trade secrets, which, by its title, showed the existence of the belief that the "right use of alchemy" was to bring chemical knowledge to bear upon industry. The earliest edition was published in 1531,[3] and the first English translation in 1583, from which the following extracts may be of interest. "Take snayles, and first drawne water of a red die of which water being taken in the two firste moneths of haruest when it raynes," boil it with the snails, "then heate your iron red hote and quench it therein and it shall be hard as steele." "Ye may do the like with the blood of a man of xxx yeres of age, and of sanguine complexion, being of a merry nature and pleasaunt . . . distilled in the middst of May." This may seem trivial enough, but the belief in the efficacy of such solutions survived into the present century, for I find in a work[4] published in 1810 that the artist is prettily directed "to take the root of blue lilies, infuse it in wine and quench the steel in it," and the steel will be hard; on the other hand, he is bewilderingly told that if he "takes the juice or water of common beans and quenches iron or steel in it, it will be soft as lead." As must always be the case when the practice of an art is purely empirical, such procedure was often fantastic, but it is by no means obsolete, for probably at the present day there is hardly a workshop in which some artificer could not be found with a claim to possess a quaint nostrum for hardening steel. Even the use of absurdly compounded baths, to which I have referred, was supported by theoretical views. Otto Tachen,[5] for instance, writing of steel in about the year 1666, says that steel when it is "quenched in water acquires strength because the light alcaly in the water is a true comforter of the light acid in the iron, and cutlers do strengthen it with the alcaly of animals"; hence the use of snails. Again, Lemery[6] explains in much the same way the production of steel by heating iron in the presence of horns of animals.

I have dwelt so long on these points in order to bring out clearly the fact

[1] "La Ferronnerie," par F. Liger, t. ii., p. 147 (Paris, 1875).

[2] "Diversarum Artium Schedula," vol. iii., chap. xxi.

[3] "Rechter Gebrauch d. Alchimei," 1531. There were many English editions, the earliest being "A profitable boke declaring dyuers approoued remedies," etc. (London, 1583). See Prof. Ferguson's learned paper "On some Early Treatises on Technological Chemistry," *Proc. Phil. Soc. of Glasgow*, Jan. 1886.

[4] "The Laboratory or School of Arts," 6th edition, 1799, p. 228. There is a later edition of 1810.

[5] "His Key to the Ancient Hippocratical Learning," p. 68 (London, 1690).

[6] "A Course of Chemistry," 2nd edition, 1686, p. 131.

that the early workers attached great importance to the nature of the fluid in which hot steel was quenched, and they were right, though their theories may have been wrong. The degree of rapidity with which heat is abstracted from the steel during the operation of hardening is as important at the present day as it ever was. Roughly speaking, if steel has to be made glass-hard, ice-cold water, brine, or mercury is used; if it has only to be made slightly hard, hot water or oil may be employed; while, as Thomas Gill [1] suggested in 1818, both "hardening" and "tempering" may be united in a single operation by plunging the hot metal in a bath of molten lead or other suitable metal, which will of course abstract the heat more slowly.

The use of lead and other metals in hardening steel has, however, long been known. Réaumur [2] described in 1722 a method of hardening the points of tools by forcing them when red hot into *solid* tin and lead, and he hints at the use of solid masses of gold, silver, and copper as cooling metals. This old work blends curiously into the new, for the cold metallic surfaces suggested by Clémendot [3] doubtless play an important part in his process of hardening by compression; while another process, that of hardening by water-spray, of which much has been heard recently in connection with the manufacture of artillery, is at least a century old, for Guyton de Morveau [4] said that "*l'air refraichi par la vapeur humide d'une cascade, durcit très bien, suivant M. Perret.*" In recent years Jarolimek [5] has studied the conditions under which the process may be practised with success, the vaporisation of the fluid appearing to be all-important.

I have not met with an earlier reference to the use of mercury as a cooling fluid than that made by Réaumur, but in no direction has the modern development of hardening processes been more important than in connection with the use of baths in which the fluid, being a molten metal, is not readily vaporised. M. Lisbonne,[6] formerly Directeur des Constructions Navales in France, has shown what remarkable results as regards resistance to penetration have attended the adoption of the process of hardening armour-plates in lead baths, which, as M. Alfred Everard [7] shows, must be capacious and not heated much above the melting point of lead, his experiments leading to the conclusion that armour-plates so quenched in lead are both very difficult to penetrate and present great resistance to fracture. The use of metallic baths both for hardening and tempering is giving rise to problems of great complexity and interest.

We must now trace the development of theories relating to the internal constitution of steel. The advent of the phlogistic school with the teaching of Becher and Stahl led to the view that iron gained phlogiston during its conversion into steel. By phlogiston we know that the early chemists really meant *energy*, but to them phlogiston was represented to be a kind of soul possessed by all metals, which they could lose by burning and regain by the

[1] *Thomson's Annals of Philosophy*, xii., 1818, p. 58.
[2] "L'art de convertir le fer forgé en acier, p. 351 (Paris, 1722).
[3] *Comptes rendus*, xciv., 1882, p. 703.
[4] Article "Acier," *Encyc. Méthodique*, p. 436 (Paris, 1786).
[5] *Oesterreiche Zeitschrift für Berg- und Hüttenwesen*, 1876, pp. 70, 84.
[6] *Génie Civile*, vol. xiii., 1888, p. 22.
[7] "De l'emploi des bains métalliques dans le traitement final des grosses pièces en acier," paper read at the International Congress of Mining and Metallurgy, Paris, 1889.

process they called "revivification." "Hardness [in metals] is caused by the jeiunenese of the spirit and their imparity with the tangible parts," said Francis Bacon;[1] while, according to Stahl,[2] steel was merely iron possessing in virtue of its phlogiston, the characteristics of a metal in a higher degree; and this view prevails in the writings of Henckel, Newmann, Cramer, Gellert, Rinman, and Macquer. This opinion survived with wonderful persistence, but it did not influence the teaching of Réaumur,[3] who, in 1722, was, so far as I know, the first to suggest a physical theory which has been in any way justified by modern research. He assumed that when steel was heated "sulphurs and salts" were driven out from the molecules, which he represents diagrammatically, into the interstitial space between them. The quenching of the steel and its sudden cooling prevented the sulphurs and salts from returning into the molecules, which were thus firmly cemented by the matter between them, and hard rigid steel was the result. In tempering, the sulphurs and salts partially returned into the molecules, and the metal became proportionately soft. I have elsewhere shown[4] that he used the Torricellian vacuum to demonstrate that the hardening of steel is not accompanied by the evolution of gas, and he concluded that "since the hardening of steel is neither due to the intervention of a new substance nor to the expulsion of air, it only remains to seek its cause in the changes occurring in its structure." Notwithstanding this, the phlogistic school were not daunted, and this brings me to the work of Torbern Bergman, the great Professor at the University of Upsala, who in 1781 showed[5] that steel mainly differs from iron by containing about $\frac{2}{10}$ per cent. of plumbago, while iron does not. Read in connection with modern research, his work seems wonderfully advanced. He was so forcibly impressed by the fact that the great difference in the mechanical properties of different specimens of iron is due to the presence of small quantities of impurity, and that the properties of iron do not vary, as he says, unless by chance the iron has gathered foreign matter, "*nisi forte peregrinum paullo uberius inhærat metallum.*" We find, even, the dawn of the view that under the influence of small quantities of foreign matter iron is, as he calls it, polymorphous, and plays the part of many metals. "*Adeo ut jure dici queat, polymorphum ferrum plurium simul metallorum vices sustinere.*"[6] Unfortunately he confounded the plumbago or carbon he had isolated with phlogiston, as did Rinman in 1782, which was strange, because, in 1774, the latter physicist had shown that a drop of nitric acid simply whitens wrought iron, but leaves a black stain on steel. Bergman tenaciously held to the phlogistic theory in relation to steel; it was inevitable that he should. The true nature of oxidation had been explained; no wonder that the defenders of the phlogistic theory should seek to support their case by appealing to the subtle and obscure changes produced in iron by such apparently slight causes. Bergman's view was, however, combated by Vandermonde, Berthollet,

[1] "Sylva Sylvarum," 2nd edition, 1628, p. 215.

[2] "Fundamenta Chemiæ," Part 3, p. 451, quoted by Guyton de Morveau in the article "Acier," *Encyc. Méthodique*, p. 421. Paris, 1786.

[3] "L'art de convertir le fer forgé en acier," p. 321 *et seq.* Paris, 1722.

[4] *Proc. Inst. Mech. Engineers*, Oct. 1881, p. 706. See also pp. 235-238.

[5] "Opuscula Physica et Chemica," vol. iii., "De Analysi Ferri" (Upsala, 1783). A dissertation delivered June 9, 1781.

[6] "De Analysi Ferri," p. 4.

and Monge,[1] who showed in a report communicated to the Académie des Sciences, in 1786, that the difference between the main varieties of iron is determined by variation in the amount of carbon, and further that steel must contain a certain quantity of carbon in order that it might possess definite qualities. Bergman died in 1784, and the report to which I have referred is full of respect for "this grand chemist," as its authors call him, "whom science has lost too soon."

Kirwan's essay on phlogiston,[2] in which Bergman's views were defended, elicited a reply from Lavoisier himself, and brought down the French school in strength to contest almost the last position occupied by the believers in phlogiston.[3]

An entire lecture might be profitably devoted to Bergman's work. His was almost the first calorimetric research, and it is impossible to read it without feeling that in paying the just tribute to Lavoisier's genius Bergman has been overlooked. He desired to ascertain whether pure iron, steel, and cast iron contain the same amount of heat. He, therefore, attacked the materials with a solvent, and noted the heat evolved. He says the solvent breaks up the assemblage of the aggregation of molecules and forms other unions. If the new body demands more heat than the body which has been disunited, then the thermometer will fall. If, on the other hand, the degree of heat required is less, the environment will be heated, which will result in the rise of the thermometer. The modern development is that, when a chemical compound is formed, heat is evolved and energy is lost, but if one substance, say a metal, simply dissolves another, the solution is attended with absorption of heat, and the product when attacked by a suitable solvent should evolve practically the same amount of heat, but certainly not less than would be evolved by the individual metals present in solution.[4] This is specially interesting from its relation to the calorimetric work of Lavoisier and Laplace in 1780 and of Lavoisier in 1782, which led the latter to explain the nature of oxidation, and to show that a metal could be as truly "calcined" or oxidised by the action of a solution as by the action of air at an elevated temperature. It is singular, however, that while referring fully to Bergman's work, Lavoisier should have incautiously attributed the hardening of steel to the rapid cooling of metal containing "ethiops martial" (oxide of iron) which forms incidentally during the process.[5] We are, however, mainly concerned with the fact that Bergman taught us that the difference between iron and steel consists in the $\frac{2}{10}$ to $1\frac{1}{2}$ per cent. of carbon which steel contains.

[1] "Histoire de l'Académie Royale des Sciences," 1786 (printed 1788), p. 132.

[2] R. Kirwan, "Essay on Phlogiston and the Constitution of Acids," p. 134, 1787.

[3] "Essai sur le Phlogistique," traduit de l'Anglois de M. Kirwan, avec des notes de MM. de Morveau, Lavoisier, de la Place, Monge, Berthollet, et de Fourcroy. Paris, 1788.

[4] See French translation of Bergman's work, p. 72. Paris, 1783. The question is, however, so important that I append the original Latin text:—"Menstruo laxatur compages molecularum, et nova formantur connubia, quæ, si majorem, quam diruta, figunt materiæ caloris quantitatem, in vicinia calor ad restituendum æquilibrium diminuatur oportet, et thermometri hydrargyrum ideo subsidet; si minorem, differentia liberatur et viciniam calefacit, unde etiam adscendit thermometri liquor; si denique nova connubia eamdem præcise quantitatem postulant, quod raro accidit, nulla in thermometro videbitur variatio."—Torberni Bergman, "Opuscula Physica et Chemica," vol. iii., p. 58, 1783 ("De Analysi Ferri").

[5] *Mémoires de l'Académie Royale des Sciences*, 1782, p. 556.

It was only natural that Black,[1] writing in 1796, should have attributed the hardening of steel to the "extrication of latent heat"; "the abatement of the hardness by the temper" being due, he says, "to the restoration of a part of that heat." Black failed to see that the work of Bergman had entirely changed the situation. The next step was made in France. It was considered necessary to establish the fact that carbon is really the element which gives steel its characteristic properties, and with this object in view, Clouet,[2] in 1798, melted a little crucible of iron, weighing 57·8 grammes, containing a diamond weighing 0·907 gramme, and obtained a fused mass of steel.

His experiment was repeated by many observers, but the results were open to doubt from the fact that furnace gases could always obtain access to the iron, and might, as well as the diamond, have yielded carbon to the metal. The carbon might have been presented to the iron in the form of a gas capable of yielding carbon, and this element would as surely have found its way into the steel.

Margueritte,[3] for instance, in 1865, repeated Clouet's experiment, and showed that, although carburisation can be effected by simple contact of iron and carbon, it is nevertheless true that in the ordinary process of cementation the gas carbonic oxide plays an important part, which had until then been overlooked. The discovery by Graham,[4] in 1866, of the occlusion of carbonic oxide by iron, gave additional support to this theory. I am glad to remember that he entrusted the experiments to me.

The question, however, of the direct carburisation of iron by the diamond has never been doubted since 1815, when a working cutler, Mr. Pepys,[5] heated iron wire and diamond dust together and obtained steel, the heat being afforded by a powerful electric battery.

Do not think for a moment that the steel owes its hardness to the passage of diamond into the iron, *as diamond*. I have repeated Margueritte's form of Clouet's experiment, using, however, a vacuum instead of an atmosphere of gas. [An image of the carburised iron which was the result of the experiment was thrown upon the screen.] The diamond by union with iron has passed partially at least to the other form of carbon, graphite, while treatment with a solvent which removes the iron shows that carbon has entered into intimate association with the iron, a fact which leads us to the next step in the study of the relations between carbon and iron.

Hempel[6] has shown that, in an atmosphere of nitrogen, iron appears to assimilate the diamond form of carbon more readily than either the graphitic or the amorphous forms, but directly carbon is associated with *molten* iron it behaves like the protean element it is, and the state which this carbon assumes is influenced by the rate of cooling of the molten mass, or even by the thermal treatment to which the solidified mass is subjected. Let me repeat, all are familiar with carbon in the distinct forms of diamond, graphite, and soot; all are alike carbon. It need not be considered strange, then,

[1] "Lectures on the Elements of Chemistry," vol. ii., p. 505, 1803.
[2] Experiment described by Guyton de Morveau, *Ann. de Chim.*, vol. xxxi., 1799, p. 328.
[3] "Sur l'aciération," *Ann. Chim. et Phys.*, t. vi. (4), 1865.
[4] *Phil. Trans. Roy. Soc.*, 1866, pp. 399-439.
[5] *Ibid.*, 1815, p. 371.
[6] *Ber. der deutsch. chem. Gesellschaft*, vol. xviii., p. 998.

that carbon should be capable of being present in intimate association with iron, but in very varied forms.

Now the mode of existence of carbon in soft annealed steel is very different from that in which it occurs in hard steel. I believe that Karsten was the first to isolate, in 1827, from soft steel a true compound of iron and carbon. Berthier [1] also separated from soft steel a carbide of iron, to which he assigned the formula FeC; but to attempt to trace the history of the work in this direction would demand an entire lecture. I will only add that within the last few years Sir F. Abel has given much experimental evidence in favour of the existence in soft cold-rolled steel of a carbide, Fe_3C, which he isolated by the slow solvent action of a chromic acid solution. His work has been generally accepted as conclusive, and has been the starting point of much that has followed.

It will occur to you that the microscope should reveal wide differences between the structure of various kinds of iron and steel, and I am happy to be able to give you enlarged diagrams made from the drawings of Mr. Sorby, the eminent microscopist, which illustrated his very delicate investigations into the structure of steel.[2]

The point I am mainly concerned with is the existence of a substance which Sorby called the "pearly constituent" in soft steel. This pearly constituent is closely related to the carbide of iron, Fe_3C of Abel,[3] and is probably a mixture of Fe_3C and pure iron. [A diagram was shown summarising the results of many experiments.]

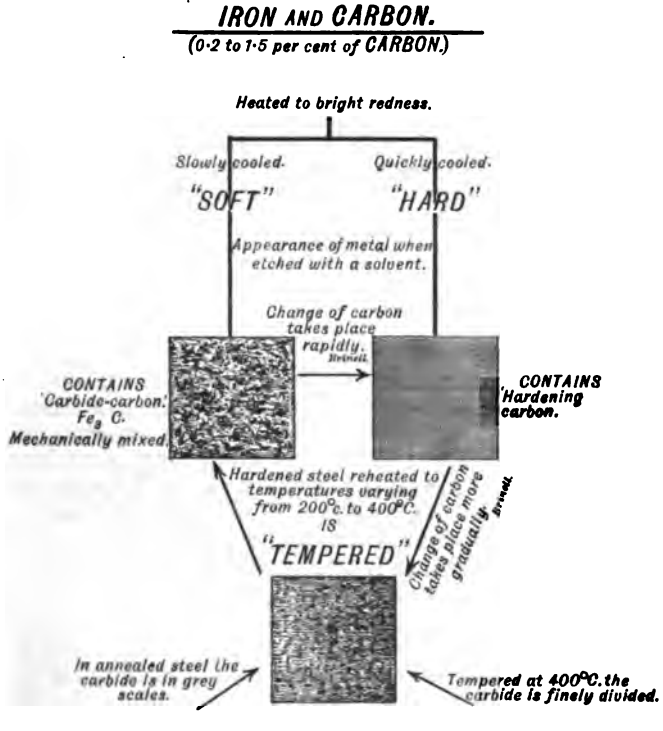
A study of this diagram and of the admirable work of Prof. Ledebur [4] will show how complex the relations of carbon and iron really are, but, for the purposes of the present inquiry, it may fairly be asked, Does a change in the "mode of existence" of carbon in iron sufficiently explain the main facts of hardening and tempering? It does not. It is possible to obtain by rapid cooling from a certain temperature steel which is perfectly soft, although analysis proves that the carbon is present in the form which we have recognised as "hardening carbon." No doubt in the hardening of steel the carbon changes its mode of existence, but we must seek some other theory to explain all the facts, and in order to do this we will turn to the behaviour of the iron itself.

In approaching this portion of the subject a few elementary facts relative to the constitution of the matter must be recalled, and in doing so I must again appeal briefly to history. It is universally accepted that metals, like all elements, are composed of atoms of definite weights and volumes grouped in molecules. In order actually to transmute one metal into another it would be necessary to discover a method of attacking not the molecule but the *atom*, and of changing it, and this, so far as is known, has not yet been done; but it is possible, by influences which often appear to be very slight, to change the relations of the molecules to each other, and to alter the arrangements or distribution of the *atoms* within the *molecules*, and by varying in this sense the molecular arrangement of certain elements, they may be made to pass into forms which are very different from those in which we ordinarily know

[1] *Ann. des Mines*, t. iii., 1833, p. 229.
[2] The reader must refer to the *Journ. of the Iron and Steel Inst.*, No. 1, 1887, p. 255.
[3] *Proc. Inst. Mech. Engineers*, Jan. 1883.
[4] *Stahl und Eisen*, vol. viii., 1888, p. 742.

them. Carbon, for instance, when free, or when associated with iron, may readily be changed from the diamond to the graphitic form, though it is uncertain whether the converse change has as yet been effected.

Sulphur, again, with which you are familiar as a hard, brittle, yellow solid, may be prepared and maintained for a little time in the form of a brown viscous mass, but this latter form of sulphur passes spontaneously and slowly at the ordinary temperature, and instantaneously at 100°, to the solid octahedral yellow modification with evolution of heat. The viscous form of sulphur is an allotropic modification of that element. A few cases of allotropy in metals have already been established, and when they do occur they give rise to problems of vast industrial importance. Such molecular



changes in metals are usually produced by the addition of a small quantity of foreign matter, and I have elsewhere tried to show that the molecular change produced by the action of *traces* upon *masses* is a wide-spread principle of nature, and one which was recognised at the dawn of the science of chemistry, even in the seventh century, although distorted explanations were given of well-known facts, and gave rise to entirely false hopes. But it is the same story now as in mediæval times: the single grain of powder which Raymond Lully said would transmute millions of its weight of lead into gold—the single grain of stone that Solomon Trismosin thought would secure perpetual youth—had their analogues in the small amount of plumbago which, to Bergman's astonishment in the eighteenth century, converted iron into

steel. By his time it was recognised that "the right use of alchemy" consisted in the application of its methods to industry, and we still wonder at the minuteness of the quantity of certain elements which can profoundly affect the properties of metals. The statements are true, and are not derived from poetical literature, early or late. Even in the moral world the significance of the action of traces upon masses has been recognised, and the method of the alchemist survives in the administration of the small quantity of powder which, in the imagination of Robert Louis Stevenson, will produce the malevolent Hyde modification of the benevolent Dr. Jekyll. In thus borrowing an illustration from one of the most refined and subtle writers of our time, I do not fear the taunt of Francis Bacon,[1] that "sottishly do the chymics appropriate the fancies and delights of poets in the transformation of bodies to the experiments of their furnaces"; for, although it may not be possible to *transmute* metals, it is easy so to *transform* them, by very slight influences, that as regards special service required from them they may behave either usefully or entirely prejudicially.

In attempting to illustrate this part of the subject I cannot take the most striking cases, as it is difficult to demonstrate them in the time at my disposal. The following experiment, which does not, however, depend upon the action of a trace upon a mass, will enable me to lead up to the point I wish to insist upon. It consists in the release of gold from its alloy with potassium. When the alloy is treated with water, the gold comes down in a finely divided, dark brown, chemically active state. [Experiments shown on the screen.]

I have chosen this experiment because it was a similar one that first roused suspicion that pure iron could exist in more than one form.

The question at once suggests itself, Can iron behave in a similar manner: is an allotropic form of iron known? Joule afforded experimental evidence for an affirmative answer to this question nearly forty years ago by communicating to the British Association in 1850 a paper "On some Amalgams." The result of his experiments, published in detail later,[2] in a paper which has been sadly neglected, showed that iron released from its amalgam with mercury is chemically active, as it combines readily with the oxygen of the air at the ordinary temperature, and he claims that the iron so set free is allotropic; but Joule did much more than this. Magnus had shown (1851) that the thermo-electric properties of hard and soft steel and iron differ. Joule, in a paper on some thermo-electric properties of solids, incidentally shows that the generation of a thermo-electric current affords a method of ascertaining the degree of carburisation of iron, and he appeals to the "thermo-electricity of iron in different states" as presenting a "fresh illustration of the extraordinary physical changes produced in iron by its conversion into steel," and he adds the expression of the belief "that the excellence of the latter metal might be tested by ascertaining the amount of change in thermo-electric condition which can be produced by the process of hardening."[3] It is by a thermo-electric method that the views as to the existence of iron in allotropic forms has been confirmed. Jullien, in his "Théorie

[1] Preface to the "Wisdom of the Ancients."
[2] "On some Amalgams," *Mem. Lit. Phil. Soc.*, Manchester, vol. ii. (3), p. 115.
[3] *Phil. Trans.*, vol. cxlix., 1859, p. 91.

de la Trempe,"[1] published in 1865, seems to have thought that iron can pass to an allotropic state, but he cannot be said to have added much to our knowledge, although he certainly directed attention to the importance of hardening and tempering steel.

The next step was made in Russia, in 1868. Chernoff, who has found an admirable exponent to English readers in Mr. W. Anderson, President of Section G, showed that steel could not be hardened by rapid cooling until it had been heated to a definite temperature—to a degree of redness which he called *a*. Then in 1873, Prof. Tait[2] used this expression in a Rede Lecture delivered at Cambridge: "It seems as if iron becomes, as it were, a different metal on being raised above a certain temperature; this may possibly have some connection with the ferricum and ferrosum of the chemists." He also published his now well-known "first approximation to a thermo-electric diagram," which is of great interest in view of recent work. At about this time those specially interested in this question remembered that Gore[3] had shown that a curious molecular change could be produced by heating an iron wire, which sustains a momentary elongation on cooling. Barrett repeated Gore's experiment, and discovered that as an iron wire cools down it suddenly *glows*, a phenomenon to which he gave the name *recalescence*, and these investigations have been pursued and developed in other directions by many skilful experimenters.[4] In 1879, Wrightson[5] called attention to the abnormal expansion of carburised iron at high temperatures.

The next point of special importance seems to me to be that recorded by Barus, who, by a thermo-electric method, showed, in an elaborate paper published in 1879,[6] that "the hardness of steel does not increase continuously with its temperature at the moment of sudden cooling, but, at a point lying in the dark-red heat, the glass-hard state is suddenly attained." I shall have again to refer, though but briefly, to the remarkable series of papers published by Barus and Strouhal,[7] embodying the results of laborious investigations, to which, in the limited space of this lecture, I can do but scanty justice; and finally, within the last few years, Pionchon[8] showed that at a temperature

[1] "Annexe au Traité de la Métallurgie du Fer," 1865.

[2] *Nature*, vol. viii., 1873, pp. 86, 122; and *Trans. Roy. Soc. Edin.*, vol. xxvii., 1873, p. 125.

[3] *Proc. Roy. Soc.*, vol. xvii., 1869, p. 260.

[4] G. Forbes, *Proc. Roy. Soc. Edin.*, vol. viii., 1874, p. 363: Norris, *Proc. Roy. Soc.*, vol. xxvi., 1877, p. 127; Tomlinson, *Phil. Mag.*, vol. xxiv., 1887, p. 256; vol. xxv., pp. 45, 103, and 372; vol. xxvi., p. 18; Newall, *Phil. Mag.*, vol. xxiv., 1887, p. 435; vol. xxv., 1888, p. 510.

[5] *Journ. Iron and Steel Inst.*, 1879, No. 2; 1880, No. 1.

[6] Barus, *Phil. Mag.*, vol. viii., 1879, p. 341.

[7] "Hardness (Temper), its Electrical and other Characteristics," Barus, *Phil. Mag.*, vol. viii., p. 341, 1879; *Wied. Ann.*, vol. vii., p. 383, 1879; Strouhal and Barus, *Wied. Ann.*, vol. xi., p. 930, 1880; *ibid.*, vol. xx., p. 525, 1883. "Hardness and Magnetisation," *Wied. Ann.*, vol. xx., pp. 537, 662, 1883. "Density and (Internal) Structure of Hard Steel and of Quenched Glass," Barus and Strouhal, *American Journ.*, vol. xxxi., p. 386, 1886; *ibid.*, p. 439; *ibid.*, vol. xxxi., p. 181, 1886. "Temper and Chemical Composition," *Am. Journ. Sci.*, vol. xxxii., p. 276, 1886. "Temper and Viscosity," *Am. Journ.*, vol. xxxii., p. 444, 1886; *ibid.*, vol. xxxiii., p. 20, 1887; Barus, *ibid.*, vol. xxxiv., p. 1, 1887; *ibid.*, vol. xxxiv., p. 175, 1887. These papers, systematically discussed and enlarged, are embodied with new matter in the *Bulletins* of the United States Geological Survey, viz.:—*Bull.*, No. 14, pp. 1-226, 1885; *Bull.*, No. 27, pp. 30-61, 1886; *Bull.*, No. 35, pp. 11-60, 1886; *Bull.*, No. 42, pp. 98-131, 1887.

[8] *Comptes rendus*, vol. cii., 1886, pp. 675 and 1454; vol. ciii., p. 1122.

of 700° the specific heat of iron is altogether exceptional, and Le Chatelier [1] has detected that at the same temperature a change occurs in the curve representing the electromotive force of iron—both experimenters concluding that they had obtained evidence of the passage of iron into an allotropic state.

Osmond,[2] in France, then made the observations of Gore and Barrett the starting point of a fresh inquiry, which will now be considered at some length, as Osmond has arrived at conclusions of much interest and importance.

The following considerations appear to have guided Osmond in beginning his investigations. Bearing in mind the fact that molecular change in a body is always accompanied by evolution or absorption of heat, which is, indeed, the surest indication of the occurrence of molecular change, he studied with the aid of a chronograph what takes place during the slow cooling and the slow heating of masses of iron or steel, using, as a thermometer to measure the temperature of the mass, a thermo-electric couple of platinum and of platinum containing 10 per cent. of rhodium, converting the indications of the galvanometer into temperatures by Tait's formulæ.

[Curves were then shown illustrating the variations in temperature during the cooling of different samples of steel.]

[In the experiments shown to the audience the spot of light moved slowly and uniformly along the screen 10 feet in length. It halted for a few seconds as the temperature of the cooling mass of steel fell to about 850° C., and when the metal was at full redness, the spot of light remained stationary, for 68 seconds, and then resumed its course.]

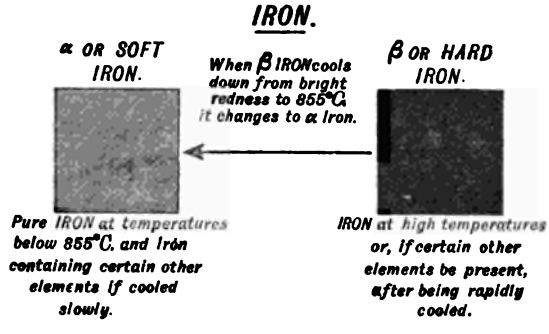
Now, it may be urged, evidently the presence of carbon has an influence on the cooling of steel when left to itself: may it not affect molecular behaviour during the rapid cooling which is essential to the operation of hardening? We know that the carbon, during rapid cooling, passes from the state in which it is combined with the iron into a state in which it is dissolved in the iron; we also know that, during slow cooling, this dissolved carbon can re-enter into combination with the iron so as to assume the form in which it occurs in soft steel. Osmond claims that this second arrestation in the fall of the thermometer corresponds to the recalescence of Barrett, and is caused by the reheating of the wire by the heat evolved when carbon leaves its state of solution and truly combines with the iron.

If it is hoped to *harden* steel, it must be rapidly cooled before the temperature has fallen to a definite point, not lower than 650°, or the presence of carbon will be unavailing. But what does the first break in the curves mean? You will see that a break occurs in electro-type iron which is free from carbon; it must then indicate some molecular change in iron itself, accompanied with evolution of heat—a change with which carbon has nothing whatever to do, for no carbon is present; and Osmond argues thus:—There are two kinds of *iron*, the atoms of which are respectively arranged in the

[1] *Ibid.*, vol. cii., p. 819.

[2] The reader will find the principal part of Osmond's work in the following papers:—Osmond et Werth, "Théorie Cellulaire des Propriétés de l'Acier," *Ann. des Mines*, vol. viii., 1885, p. 5; "Transformations du Fer et du Carbone," Paris, Baudoin et Cie., 1888; "Études Métallurgiques," *Ann. des Mines*, Juillet-Août, 1888. There is also a very interesting paper, "Sur les Nouveaux Procédés de Trempe," which he communicated to the Mining and Metallurgical Congress, Paris, 1889.

molecules so as to constitute *hard* and *soft iron*, quite apart from the presence or absence of carbon. In red-hot iron the mass may be soft but the molecules are hard—let us call this β iron; cool such red-hot pure iron, whether quickly or slowly, and it becomes soft; it passes to the α soft modification—there is nothing to prevent its doing so. It appears, however, that if carbon is present, and the metal be rapidly cooled, the following result is obtained: a certain proportion of the molecules are retained in the form in which they existed at a high temperature—the hard form, the β modification—and hard *steel* is the result. (The main facts of the case were made clearer by the aid of a diagram.) This molecular change from β iron to α iron during the slow cooling of a mass of iron or steel is, according to Osmond's theory, indicated by the first break in the curve, representing the slow cooling of iron, as is proved by the fact that it occurs alone in electro-iron. A second break, usually one of much longer duration, marks the point at which carbon itself changes from the dissolved or hardening carbon to the combined carbide-carbon. It follows that, if steel be quickly cooled *after the change from β to α* has taken place but before the carbon has altered its state—that is, before the change indicated by the second break in the curve has been reached



—then the iron should be soft, but the carbon, hardening carbon; and as such, the action of a solvent should show that it cannot be released from iron in the black carbide form. This proves to be the case, and affords strong incidental proof of the correctness of the view that two modifications of iron can exist.

It will be seen, therefore, that, although the presence of carbon is essential to the hardening of steel, the change in the mode of existence of the carbon is less important than has hitherto been supposed.

The α modification of iron may be converted into the β form by stress applied to the metal at temperatures below a dull red heat, provided the stress produces permanent deformation of the iron,[1] but the consideration of this question would demand a lecture to itself. I am anxious to show you an experiment which will help to illustrate the existence of molecular change in iron.

Here is a long bar of steel containing much carbon. In such a variety of steel, the molecular change of the iron itself, and the change in the relations between the carbon and the iron, would occur at nearly the same moment.

[1] "Etudes Métallurgiques," par Osmond, p. 6. Paris: Dunod. 1888.

It is now being heated to redness. One end of the red-hot bar will be firmly fixed and a weight *not sufficient to bend it* is slung to the free end, which is lengthened by the addition of a reed to magnify any motion that may take place. Now remember that as the bar will be red-hot it ought to be at its softest, you would think, when it is freshly withdrawn from the furnace, and if the weight was ever to have power to bend it, it would be then; but, in spite of the rapidity with which such a thin bar cools down in the air and becomes rigid, points of molecular weakness come when the iron changes from β to α, and the carbon passes from hardening carbon to carbide-carbon; at that moment, at a temperature much below that at which it is withdrawn from the furnace, the bar will begin to bend. It has been found experimentally that this bend occurs at the point at which, according to Osmond's theory, molecular change takes place. Mr. Coffin takes advantage of this fact to straighten distorted steel axles.[1]

There is a sentence in the address which has just been delivered before Section G, by Mr. Anderson, which has direct reference to molecular change in iron. He says:—

> When, by the agency of heat, molecular motion is raised to a pitch at which incipient fluidity is obtained, the particles of two pieces brought into contact will interpenetrate or diffuse into each other, the two pieces will unite into a homogeneous whole, and we can thus grasp the full meaning of the operation known as "welding."

It is, however, possible to obtain evidence of interchange of molecular motion, as has been so abundantly shown by Spring, even at the ordinary temperature, while in the case of steel, it must take place far below incipient fluidity—indeed, at a comparatively low temperature, as is shown by the following experiment on the welding of steel. Every smith knows how difficult it is to weld highly carburised hard tool-steel, but if the ends of a newly-fractured $\frac{3}{16}$-inch square steel rod are placed together and covered with platinum foil, so as to exclude the air, and if the junction is heated in the flame of a Bunsen burner the metal will weld, without pressure, so firmly that it is difficult to break it with the fingers, although the steel has not attained a red-heat.[2]

The question now arises, What is the effect of the presence of other metals in steel, of which much has been heard recently? (1) Manganese. Osmond has shown that this metal enables steel to harden very energetically, as is well known. If much of it be present, 12 to 20 per cent., in iron, *no break whatever* is observed in the curve which represents slow cooling. That is, the iron never shows such a change as that which occurs in other cooling masses of iron. Then you will say such a material should be hard however it is cooled. So it is. There is one other important point of evidence as to molecular change connected with the addition of manganese to submit to you. Red-hot iron is not magnetic. Hopkinson[3] has shown that the temperature of recalescence is that at which iron ceases to be magnetic. It may be urged that β iron cannot, therefore, be magnetised. Steel containing much manganese cannot be magnetised, and it is, therefore, fair

[1] *Trans. American Soc. Civil Engineers*, vol. xvi., 1887, p. 324.
[2] *Trans. American Soc. Mech. Engineers*, vol. ix., 1888, p. 155.
[3] *Proc. Roy. Soc.*, vol. xlv., 1889, pp. 318, 445, and 457.

to assume that the iron present is in the β form. Hadfield [1] has given metallurgists wonderful alloys of iron and manganese in proportions varying from 7 to 20 per cent. of manganese. This core, or iron, round which a current is passing, attracts the sphere of iron, but if nothing is changed, except by replacing the core of iron with a core of Hadfield's steel, it is impossible to make a magnet of it. [Experiment shown.]

Prof. Ewing, who has specially worked on this subject, concludes that, "no magnetising force to which the metal is likely to be subjected in any of its practical applications would produce more than the most infinitesimal degree of magnetisation" in this material.

It has been seen that quantities of manganese above 7 per cent. appear to prevent the passage of β iron into the α form. In smaller quantities manganese seems merely to retard the conversion, and to bring the two loops of the diagram nearer together.

Time will not permit me to deal with the effect of other elements on steel. I will only add that tungsten possesses the same property as manganese, but in a more marked degree. Chromium has exactly the reverse effect, as it enables the change of hard β iron to α soft iron to take place at a higher temperature than would otherwise be the case, and this may explain the extreme hardness of chromium steels when hardened in the same way as ordinary steels.

There are a few considerations relative to the actual working of steel with which I can deal but briefly, notwithstanding their industrial importance. The points *a* and *b*, adopted in the celebrated memoir of Chernoff to which I have referred already, change in position with the degree of carburisation of the metal. It is useless to attempt to harden steel by rapid cooling if it has fallen in temperature below the point (in the red) *a*, and this is the point of "recalescence" at which the carbon combines with the iron to form carbide-carbon: it is called V by Brinell. In highly carburised steel, it corresponds exactly with the point at which Osmond considers that iron, in cooling slowly, passes from the β to the α modification. Now with regard to the point *b* of Chernoff. If steel be heated to a temperature above *a*, but below *b*, it remains fine-grained however slowly it is cooled. If the steel be heated above *b*, and cooled, it assumes a crystalline granular structure whatever the rate of cooling may be. The size of the crystals, however, increases with the temperature to which the steel has been raised.

These critical changes, produced in carburised iron by thermal treatment, have been observed by Sorby with the aid of the microscope, and have been dealt with in his usual careful way.

Now the crystalline structure, which is unfavourable to the steel from the point of view of its industrial use, may be broken up by the mechanical work of forging the hot mass; and the investigations of Abel, of Maitland, and of Noble have shown how important "work" on the metal is. When small masses of hot steel are quenched in oil, they are hardened just as they would be if water were used as a cooling fluid. With large masses, the effect of quenching in oil is different. Such cooling of large hot masses appears to break up this crystalline structure in a manner analogous to mechanical working. If the mass of metal is very large, such as a propeller shaft, or tube of a large gun, the change in the relations between the carbon and the

[1] *Proc. Inst. Civil Engineers*, vol. xcii., Part iii., 1888.

iron, or true "hardening" produced by such oil treatment is only effected *superficially*—that is, the hardened layer does not penetrate to any considerable depth, but the innermost parts are cooled more quickly than they otherwise would have been, and the development of the crystals, which would have assumed serious proportions during slow cooling, is arrested. It depends on the size of the quenched mass, whether the tenacity of the metal is or is not increased, but its power of being elongated is considerably augmented. This prevention of crystallisation I believe to be the great merit of oil quenching, which, as regards large masses of metal, is certainly not a true hardening process.

There has been much divergence of view as to the relative advantages of work on the metal, and of oil-hardening, but I believe it will be possible to reconcile these views, if the facts I have so briefly stated be considered.

The effect of annealing remains to be dealt with. In a very complicated steel casting, the cast metal probably contains much of its carbon as hardening carbon, and the mass which has necessarily been poured into the mould at a high temperature is crystalline. The effect of annealing is to permit the carbon to pass from the "hardening" to the "carbide" form, and, incidentally, to break up the crystalline structure, and to enable it to become minutely crystalline. The result is that the annealed casting is far stronger and more extensible than the original casting. The carbide-carbon is probably interspersed in the iron in fine crystalline plates, and not in a finely divided state. It would obviously be impossible to "work"—that is, to hammer—complicated castings, and the extreme importance of obtaining a fine crystalline structure by annealing, with the strength which results from such a structure, has been abundantly demonstrated by Mr. J. W. Spencer, whose name is so well known to you all in Newcastle.

The effect of annealing and tempering is in fact very complicated, and I can only again express my wish that it were possible to do justice to the long series of researches which Barus and Strouhal have conducted in recent years. They consider that annealing is demonstrably accompanied by chemical change, even at temperatures slightly above the mean atmospheric temperature, and that the "molecular configuration of glass-hard steel is always in a state of incipient change, . . . a part of which change must be of a permanent kind." Barus[1] says "that during the small interval of time within which appreciable annealing occurs, a glass-hard steel rod suddenly heated to 300° is almost a viscous fluid," and he considers that glass-hard steel is constantly being spontaneously "tempered" at the ordinary temperature, which, he says, "acting on freshly quenched [that is, hardened] steel for a period of years, produces a diminution of hardness about equal to that of 100° C., acting for a period of hours."

The nature of the molecular change is well indicated in the long series of researches which led them to conclude that in steel "there is a limited interchange of atoms between molecules under stress, which must be a property common to solids, if, according to Maxwell's conception, solids are made up of configurations in all degrees of molecular stability."

Barus and Strouhal attach but little importance to the change in the relations between the carbon and the iron during the tempering and annealing

[1] *Phil. Mag.*, vol. xxvi., 1888, p. 209.

of hard steel. They consider that in hardening steel the "strain once applied to steel is locked up in the metal in virtue of its viscosity"; tempering is the release of this molecular strain by heat.

Highly carburised steels harden very energetically by very slight modifications in thermal treatment, and it will be evident that a very hard material is unsuitable for industrial use if the conditions of its employment are such as to render it desirable that the material should stretch. To turn to very "mild" steel which hardens but little, it is certain that, although wrought iron passes almost insensibly into steel, there can be no question that not merely the structural but the molecular aggregation of even steel containing only $\frac{2}{10}$ per cent. of carbon is profoundly different from that of wrought iron. Formerly, as Sir F. Bramwell pointed out in a lecture delivered at the Royal Institution in 1877, "by the year 1830 . . . from small beginnings in Staffordshire and at Birkenhead sprang a wonderful *wrought-iron* navy, but steel was a luxury: it was made in small portions sold at high prices, as much as a shilling or eighteenpence a pound. It was employed for swords, cutlery, and tools, needles, and other purposes where the quantity used was but trifling, and where the importance of the superior material was such as to justify the large expenditure incurred. It was felt in those days that steel was worth paying for, because it was trusted; indeed its trustworthiness had passed into a proverb"—"as true as steel."

This class of steel which was formerly employed, as I have just indicated, for weapons and tools belonged to the highly carburised, readily-hardening class. It was the "mild steel" containing but little carbon which was destined to replace wrought iron, and when attempts were made to effect the general substitution of steel for iron, fears as to its character and trustworthiness unfortunately soon arose, so that from about the year 1860 until 1877 steel was viewed with suspicion. We can now explain this. Doubts as to the fidelity of steel, even when it was obtained free from entangled cinder, arose from ignorance of the fact that, on either side of a comparatively narrow thermal boundary, the iron in steel can practically exist in two distinct modifications. The steel was true enough, but from the point of view of the special duties to be intrusted to it, its fidelity depended on which modification of iron had to be called to the front. Artificers attempted to forge steel after it had cooled down below the point *a* of Chernoff, at which recalescence occurs, and they often attempted to work highly carburised steel at temperatures which were not sufficiently low.

Steels may be classified from the point of view of their industrial use according to the amount of carbon they contain, and I have attempted to arrange in this "trophy" certain typical articles, grouped under certain definite percentages of carbon ranging from $\frac{2}{10}$ to $1\frac{1}{2}$ per cent. [This was a trophy 18 feet square, with various typical articles of steel arranged in order according to the amount of carbon they contained]. I am greatly indebted to Mr. J. W. Spencer, of Newcastle, who kindly lent me the fine series of specimens of which the trophy is built up. Each class merges into the other, but the members at either end of the series vary very greatly. It would be impossible to make a razor which would cut from boiler plate; and conversely, a boiler made of razor steel would possibly fracture at once if it were superheated and subjected to any sudden pressure of steam. Speaking generally, if the steel contains, in addition to carbon, $\frac{5}{10}$ per cent. of manganese,

each class of steel, as at present arranged, would have to be shifted a class backwards towards the left of the trophy.

At the present day (1889), instead of steel being manufactured and used in small quantities, about 4,000,000 tons are annually employed in this country. Let us see how it is used. A steel fleet, the finest fleet in the world, has recently assembled at Spithead. The material of which it was made contained $\frac{15}{100}$ to $\frac{2}{10}$ per cent. of carbon, and when steel faces are used for the armour plates, the material contains $\frac{7}{10}$ to $\frac{8}{10}$ per cent. of carbon.

It has been pointed out that the crews of the fleet at Spithead numbered no less than 21,107 men. This it has been shown is "a remarkable figure, considering the great economy in men which prevails in a modern navy as compared with the navy of Nelson's day. A hundred years ago the normal requirements of a fleet were one man to a little over 4 tons, but now, thanks to the part played by steel and hydraulic power, we require but one man to every 17 tons. Thus it may roughly be said that an aggregate of 20,000 men at the present day corresponds to an aggregate of 80,000 men in the days of Nelson." The latest type of battleship (1889) weighs, fully equipped, about 10,000 tons, there being about 3,400 tons of steel in the hull, apart from her armour, which, with its backing, will weigh a further 2,800 tons.[1]

From the use of steel in the Royal Navy and in the mercantile marine, let us pass on to its most notable use in construction. If the President of the French Republic was justified in appealing, in a recent speech, to the Eiffel Tower as "a monument of audacity and science,"[2] what are we to say of the Forth Bridge, the wonders of which will be described by Mr. Baker on Saturday? By his kindness I am able to place in the position in the trophy justified by the carbon it contains, a plate from the Forth Bridge, which fell from a height of some 350 feet, and, being of excellent quality, doubled itself on the rocks below. A single span of the Forth Bridge is nearly as long as two Eiffel Towers turned horizontally and tied together in the middle, and the whole forms a complicated steel structure weighing 15,000 tons, erected without the possibility of any intermediate support, the lace-like fabric of the bridge soaring as high as the top of St. Paul's. The steel of which the compression members of the structure are composed contains $\frac{23}{100}$ per cent. of carbon and $\frac{69}{100}$ per cent. of manganese. The parts subjected to extension do not contain more than $\frac{19}{100}$ per cent. of carbon.[3]

Time will not permit me to pass the members of each class in review. I can only refer to very few. Steel for the manufacture of pens contains about $\frac{3}{10}$ per cent. of carbon, and 16 to 18 tons of steel are every week let loose on an unoffending world in the shape of steel pens.

Steel rails contain from $\frac{3}{10}$ to $\frac{4}{10}$ per cent. of carbon, and, in this class, slight variations in the amount of carbon are of vital importance. An eminent authority, Mr. Sandberg, tells us that in certain climates a variation of $\frac{1}{10}$ per cent. in the amount of carbon may be very serious. The great benefit which has accrued to the country from the substitution of more durable steel rails for the old wrought-iron ones may be gathered from the figures which Mr. Webb, of Crewe, has given me, which show that "the

[1] Address by Mr. Baker, Section G, *British Association Report*, 1885, p. 1182. Compare "Developments in Battleship Design" (*Engineering*, Oct. 11, 1912).

[2] *Times*, Aug. 19, 1889.

[3] *Journ. of the Iron and Steel Inst.*, 1888, vol. ii., p. 94.

quantity of steel removed from the rails throughout the London and North-Western system by wear and oxidation is about 15 cwts. an hour, or 18 tons a day."

Gun-steel contains $\frac{3}{10}$ to $\frac{5}{10}$ per cent. of carbon, and it may contain $\frac{8}{10}$ per cent. of manganese. It is in relation to gun-steel that oil-hardening becomes very important. The oil-tank of the St. Chamond Works (on the Loire) is 72 feet deep, and contains 44,000 gallons of oil, which is kept in circulation by rotary pumps, to prevent the oil being unduly heated locally when the heated mass of steel is plunged into it.

Now with regard to projectiles. To quote some recent remarks of Lord Armstrong,[1] "the heaviest shot used in the *Victory* was 68 lbs., while in the *Victoria* it will be 1,800 lbs.; and, while the broadside-fire from the *Victory* consumed only 325 lbs. of powder, that from the *Victoria* will consume 3,000 lbs. The most formidable projectiles belong to the highly carburised class of steel. Shells contain 0·8 to 0·94 per cent. of carbon, and, in addition, some of these have 0·94 to 2 per cent. of chromium. The firm of Holtzer shows, in the Paris Exhibition, a shell which pierced a steel plate 10 inches thick, and was found, nearly 800 yards from the plate, entire and without flaw, its point alone being slightly distorted. Compound armour-plate with steel face, which face contains 0·8 per cent. of carbon, is, however, more difficult to pierce than a simple plate of steel.

[A prominent feature in the "trophy," among the class of highly carburised steels which contain over $\frac{7}{10}$ per cent. of carbon, was a fine suspended wire $\frac{8}{100}$ of an inch diameter, of remarkable strength, supporting a weight of $2\frac{1}{2}$ cwts., or a load of nearly 160 tons to the square inch. The strength of the same steel *undrawn* would not exceed 50 tons to the square inch. A similar wire manufactured by the steel company of Firminy attracted much attention in the Paris Exhibition by supporting a shell weighing 1,800 lbs., or a load of 158 tons per square inch.]

Lastly, I will refer to the highly carburised steel used for the manufacture of dies. Such a steel should contain 0·8 to 1 per cent. of carbon, and no manganese. It is usual to water-harden and temper them to a straw colour, and a really good die will strike 40,000 coins of average dimensions without being fractured or deformed; but I am safe in saying that if the steel contained $\frac{1}{10}$ per cent. too much carbon, it would not strike 100 pieces without cracking, and if it contained $\frac{2}{10}$ per cent. too little carbon, it would probably be hopelessly distorted, and its engraved surface destroyed, in the attempt to strike a single coin.

The above examples will be sufficient to show how diverse are the properties which carbon confers upon iaon, but as Faraday said, in 1822, "It is not improbable that there may be other bodies besides charcoal capable of giving to iron the properties of steel." The strange thing is that we do not know with any certainty whether, in the absence of carbon, other elements do play the part of that metalloid, in enabling iron to be hardened by rapid cooling. Take the case of chromium, for instance: chromium-carbon steels can, as is well known, be energetically hardened, but Busek [2] has recently asserted that the addition of chromium to iron in the absence of carbon does not enable the iron to be hardened by rapid cooling. So far as I can see, it is only by employing the electrical method of Pepys that a decision

[1] *Times*, Aug. 3, 1889.

[2] *Stahl und Eisen*, vol. ix., 1889, p. 728.

can be arrived at as to the hardening properties of elements other than carbon.

For elaborate investigations of the internal strains which are developed by hardening, reference must be made to the work of the late General Kalakoutsky,[1] of the Imperial Russian Artillery, who shows that the character and value of internal stresses have a direct relation to the methods of mechanical treatment. They can be widely modified, and it is possible to indicate trustworthy and simple methods of attaining the desired results. He considers that manufacturers should take advantage of the stresses latent in masses of material with a view to increasing the strength of the product.

A few words must be devoted to the consideration of the colours which, as I said (see *ante*, p. 155), direct the artist in tempering or reducing the hardness of steel to any determinate standard. The technical treatises usually give —not always accurately, as Reiser[2] has shown—a scale of temperature ranging from 220° to 330°, at which various tints appear, passing from very pale yellow to brown-yellow, purples, and blues, to blue tinged with green, and finally to grey. Barus and Strouhal[3] point out that it is possible that the colour of the oxide film may afford an indication of the temper of steel of far greater critical sensitiveness than has hitherto been supposed. It is, however, at present uncertain how far time, temperature, and colour are correlated, but the question is being investigated by Mr. Turner, formerly one of my own students at the School of Mines.

That the colours produced are really due to oxidation was shown by Sir Humphry Davy in 1813,[4] but the nature of the film has been the subject of much controversy. Barus points out that "the oxygen molecule does not penetrate deeper than a few thousand times its own dimensions,[5] and that it probably passes through the film by a process allied to liquid diffusion. The permeable depth increases rapidly with the temperature, until at an incipient red heat the film is sufficiently thick to be brittle and liable to rupture, whereupon the present phenomenon ceases, or is repeated in irregular succession."

Looking back over all the facts we have dealt with, it will be evident that two sets of considerations are of special importance: (1) those which belong to the relations of carbon and iron, and (2) those which contemplate molecular change in the iron itself. The first of these has been deliberately subordinated to the second, although it would have been possible to have written much in support of the view that carburised iron is an alloy of carbon and iron, and to have traced with Guthrie the analogies which alloys, in cooling, present to cooling masses of igneous rocks, such as granite, which, as the temperature of the mass falls, throws off "atomically definite"[6] bodies, leaving behind a fluid mass of indefinite composition, from which the quartz and feldspar solidify before the mica. This view has been developed

[1] "Internal Stresses in Steel," G. Reveirs. London, 1888.

[2] "Das Härten des Stahles," p. 78. Leipzig, 1881. See also Lœwenherz, *Zeitschrift für Instrumentenkunde*, vol. ix., 1889, p. 322.

[3] *Bull. U.S. Geo. Survey*, No. 27, 1886, p. 51.

[4] Sir Humphry Davy, *Thomson's Ann. Phil.*, vol. i., 1813, p. 131; quoted by Turner, *Proc. Phil. Soc., Birmingham*, vol. vi., 1889, Part 2.

[5] *Bull. U.S. Geo. Survey*, No. 35, 1886, p. 51.

[6] *Phil. Mag.*, June, 1884, p. 462.

with much ability in relation to carburised iron by Prof. Howe,[1] of Boston, who even suggests mineralogical names, such as "cementite," "pearlyte," and "ferrite," for the various associations of carbon and iron.

I am far from wishing to ignore the interest presented by such analogies, but I believe that the possibility of molecular change in the iron itself, which results in its passage into a distinctive form of iron, is at present the more important subject for consideration, not merely in relation to iron, but as regards the wider question of allotropy in metals generally.

Many facts noted in spectroscopic work will have, as Lockyer has shown, indicated the high probability that the molecular structure of a metal like iron is gradually simplified as higher temperatures are employed. These various simplifications may be regarded as allotropic modifications.

The question of molecular change in solid metals urgently demands continued and rigorous investigation. Every chemist knows how much his science has gained, and what important discoveries have been made in it, by the recognition of the fact that the elements act on each other in accordance with the great law of Mendeléeff, which states that the properties of the elements are periodic functions of their atomic weights. I firmly believe that it will be shown that the relation between small quantities of elements and the masses in which they are hidden is not at variance with the same law. I have elsewhere tried to show [2] that this may be true, by examining the effect of small quantities of impurity on the tenacity of gold.

In the case of iron, it is difficult to say what property of the metal will be most affected by the added matter. Possibly the direct connection with the periodic law will be traced by the effect of a given element in retarding or promoting the passage of ordinary iron to an allotropic state; but "the future of steel" will depend on the care with which we investigate the nature of the influence exerted by various elements on iron, and the thermal treatment to which it may most suitably be subjected.

Is it not strange that so many researches should have been devoted to the relations between carbon, hydrogen, and oxygen in organic compounds, so few to the relations of iron and carbon, and hardly any to iron in association with other elements? I think that the reason for the comparative neglect of metals as subjects of research arises from the belief that methods which involve working at high temperatures are necessarily inaccurate; but the school of Ste. Claire-Deville has shown that they are not, and there are signs among us that our traditional love for the study of metals is reviving. Of course it cannot be that chemists and physicists are afraid "that science will be degraded by being applied to any purpose of vulgar utility," for I trust that I shall at least have shown that the empire over matter, and the true advancement of science, which I suppose is the object of all research, may be as certainly secured in the field of metallurgy as in any other.

[1] *Eng. and Min. Journ.*, vol. xlvi., p. 131, *et seq.* New York, 1888.
[2] *Phil. Trans. Roy. Soc.*, vol. clxxix., 1888, p. 339.

THE CONTRIBUTIONS MADE BY GREAT BRITAIN TO THE PROGRESS OF THE METALLURGY OF IRON AND STEEL DURING THE NINETEENTH CENTURY.

PRESIDENTIAL ADDRESS TO THE IRON AND STEEL INSTITUTE, 1899.[1]

The announcement that Her Majesty the Queen will be graciously pleased to accept the Bessemer medal for 1899, in commemoration of the progress made in the Iron and Steel Industries during her reign, will be received with enthusiasm throughout the Empire. What the progress has been it will be my privilege to indicate in this address; for your last President of the century, in bidding it a respectful farewell, must offer the best retrospective tribute he can to the grandest industry in the world's history.

This address will, therefore, be mainly devoted to the consideration of British efforts in connection with iron and steel. I shall hope on another occasion to pay homage to the services rendered in other countries to our branch of metallurgy, but in view of our autumn meeting last year at Stockholm, I cannot proceed further without making a brief reference to Sweden. To her scientific men our debt is great and of long standing, for we have profited by their labours from the eighteenth century until now. We appreciated the interest in our proceedings which was shown by the presence of His Majesty the King and the Royal Princes at our meetings in the Riddarhus. The gracious kindness of His Majesty during the magnificent reception at his palace of Drottningholm will never be forgotten by those of us who were present. The spontaneous warmth of our reception by the Swedish people also touched us deeply, and the memories of our visit will be handed down as traditions to future members of our Institute, who, in the days to come, will, we trust, again seek the aid of Sweden by supplementing the ores of our own possessions with those from within the Arctic circle.

It seems strange to us now to be reminded that when the nineteenth century dawned the primitive home of the iron industry in Kent, Surrey, and Sussex had not been abandoned. From my Surrey garden I look towards the tract once covered by the great forest of Anderida, within the bounds of which coal has recently been discovered. The survivors of the ancient trees of Andreds Wald still give shelter to a few charcoal-burners, the pursuit of whose occupation connects us with the past. There is almost within sound of me as I write, a stream that fed one of a series of hammer-ponds, and the district within sight is believed to have furnished the coffer for the Doomsday Book, and it certainly did the iron which encircles the cathedral of our great city. The domain has further claim to remembrance, for it supplied guns for the cruisers of Drake and Frobisher. In 1740 there were four more blast furnaces in Sussex than in any other county; in 1800 there were still two at work, and the one at Ashburnham survived until 1828, producing iron for which the claim was made that it was "in no wise inferior to the Swedish metal." These old charcoal-furnaces could rarely have exceeded 28 feet in height, with an output of some 20 tons a week. Even the greatly improved furnaces adopted about the year 1839 by John Gibbons

[1] *Journ. of the Iron and Steel Inst.*, No. 1, 1899.

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Blatchfeld,
Chilworth,
Surrey.

It was only natural that Black,[1] writing in 1796, should have attributed the hardening of steel to the "extrication of latent heat"; "the abatement of the hardness by the temper" being due, he says, "to the restoration of a part of that heat." Black failed to see that the work of Bergman had entirely changed the situation. The next step was made in France. It was considered necessary to establish the fact that carbon is really the element which gives steel its characteristic properties, and with this object in view, Clouet,[2] in 1798, melted a little crucible of iron, weighing 57·8 grammes, containing a diamond weighing 0·907 gramme, and obtained a fused mass of steel.

His experiment was repeated by many observers, but the results were open to doubt from the fact that furnace gases could always obtain access to the iron, and might, as well as the diamond, have yielded carbon to the metal. The carbon might have been presented to the iron in the form of a gas capable of yielding carbon, and this element would as surely have found its way into the steel.

Margueritte,[3] for instance, in 1865, repeated Clouet's experiment, and showed that, although carburisation can be effected by simple contact of iron and carbon, it is nevertheless true that in the ordinary process of cementation the gas carbonic oxide plays an important part, which had until then been overlooked. The discovery by Graham,[4] in 1866, of the occlusion of carbonic oxide by iron, gave additional support to this theory. I am glad to remember that he entrusted the experiments to me.

The question, however, of the direct carburisation of iron by the diamond has never been doubted since 1815, when a working cutler, Mr. Pepys,[5] heated iron wire and diamond dust together and obtained steel, the heat being afforded by a powerful electric battery.

Do not think for a moment that the steel owes its hardness to the passage of diamond into the iron, *as diamond*. I have repeated Margueritte's form of Clouet's experiment, using, however, a vacuum instead of an atmosphere of gas. [An image of the carburised iron which was the result of the experiment was thrown upon the screen.] The diamond by union with iron has passed partially at least to the other form of carbon, graphite, while treatment with a solvent which removes the iron shows that carbon has entered into intimate association with the iron, a fact which leads us to the next step in the study of the relations between carbon and iron.

Hempel[6] has shown that, in an atmosphere of nitrogen, iron appears to assimilate the diamond form of carbon more readily than either the graphitic or the amorphous forms, but directly carbon is associated with *molten* iron it behaves like the protean element it is, and the state which this carbon assumes is influenced by the rate of cooling of the molten mass, or even by the thermal treatment to which the solidified mass is subjected. Let me repeat, all are familiar with carbon in the distinct forms of diamond, graphite, and soot; all are alike carbon. It need not be considered strange, then,

[1] "Lectures on the Elements of Chemistry," vol. ii., p. 505, 1803.
[2] Experiment described by Guyton de Morveau, *Ann. de Chim.*, vol. xxxi., 1799, p. 328.
[3] "Sur l'aciération," *Ann. Chim. et Phys.*, t. vi. (4), 1865.
[4] *Phil. Trans. Roy. Soc.*, 1866, pp. 399-439.
[5] *Ibid.*, 1815, p. 371.
[6] *Ber. der deutsch. chem. Gesellschaft*, vol. xviii., p. 998.

upon its treatment, but he thought that as for the kinds of iron, they were many and all were distinct, and the first difference arises from the diversity of the soil and climate where the mines are found. But Pliny's view survived far into the present century, and evidence of it lingered in the effective and graceful speech in which the member for Merthyr proposed a vote of thanks to our first President on the delivery of his inaugural address. Mr. Fothergill said then that "thirty years ago the idea prevailed universally . . . that good iron was to be found in certain localities, and could be procured from no other place; it was found good in one place and bad in another." He adds: "Enlightened progress of the last thirty years has shown that the quality of iron depends upon the alloy with which it is mixed."

Enduring as the old view as to the influence of locality was, an experimental basis for a more accurate one had been established very shortly before the present century began, and some, at least, knew that the properties of iron depended on the presence or absence of certain other elements. This position was clearly established by the great Swedish chemist, Bergman, of Upsala, who had shown that carbon is the element to which steel and cast iron owe their distinctive properties. He had initiated the employment of calorimetric methods in determining the properties of iron and steel. He insisted that the real difficulty is to explain how it is that the presence of 0·5 per cent. of carbon in iron enables the metal to be hardened by quenching from a red heat, or, in his own expressive words, *Ceterum quomodo dimidia centesima, plumbaginem efficiens, tantam provocare possit differentiam, nodus est gordius haud facile solvendus.* Bergman, moreover, anticipated the later phases of modern research by claiming that iron is a polymorphic element, and plays the part of many metals. In this early view as to the allotropy of iron it should be remembered that in 1790 our countryman, James Keir, followed him closely by urging, before the Royal Society, that what we now call passive iron "is really a distinct form of iron, the alteration being produced without the least diminution of its metallic splendour or change of colour."

Clouet's celebrated experiment on the carburisation of iron by the diamond followed. Doubts, however, were not finally set at rest until 1815, when Pepys, a working cutler in London, excluded the possibility of the intervention of furnace gas. But, as soon as the present century had well turned, the industrial world was in possession of the fundamental fact that carbon is the element of dominant importance in relation to the metallurgy of iron. Well might Bergman express astonishment at the action of carbon on iron. Startling as the statement may seem, the destinies of England throughout the century, and especially during the latter half of it, have been mainly influenced by the use of steel. Her steel rails seldom contain more than Bergman's half per cent. of carbon. Her ship-plates, on which her strength as a maritime power depends, contain less than half that amount. It is essential that the significance of this fact should be clearly understood. Our national existence has long depended on iron and steel. They have been the source of our wealth, one of the main elements of our strength, one cause of our maritime supremacy. Hardly a step of our progress or an incident of our civilisation has not, in one way or another, been influenced by the properties of iron or steel. It is remarkable that these properties have been determined by the relations subsisting between a mass of iron, itself protean in its nature, and the few tenths per cent. of carbon it contains. These properties

are, it is true, modified either by the simultaneous presence of elements other than carbon, or by the thermal or mechanical treatment of the mass. The growth of our knowledge of the facts constitutes a large section of our scientific and industrial history. The question arises—Was our national progress delayed by the unreadiness of the technical world in England to take advantage of the facts that science had established?

If we consider the position from the point of view of two remarkable men who were looking for the dawn of the nineteenth century as we are for that of the twentieth, we shall, I think, be satisfied that our progress received no check from failure of industrial workers to assimilate the teaching of science. These men were Black and Cort. Of the scientific men then living, the greatest chemist was Black, Professor at the University of Edinburgh, whom Lavoisier had generously acknowledged as his master. Black fully recognised the importance of Bergman's work, and on his own part insisted on the importance of what would now be called the change in molecular energy as the physical basis on which the properties of iron and steel depend. Black, moreover, in his public lectures gave a singularly accurate description of the process of decarburising iron called "puddling," and devised by "a Mr. Cort," with the results of whose work Black was soon to become familiar. Considering how recent the knowledge of the meaning of oxidation really was at the time, Black's statements with regard to the theory of puddling are truly remarkable. Later on he furnished the Government with an elaborate report on the quality of the material obtained by puddling. He showed, by such mechanical tests as the experience of the time suggested, the superiority of puddled iron, and pointed out that it was more suitable than foreign iron for the appliances "on which," as he says, "the lives of our seamen and the safety of our ships have hitherto mainly depended."

At the end of the century we are justly proud of our Colonial possessions, and are satisfied that the varied applications of iron and steel will
1799. enable us to knit together all parts of the Empire. At the beginning of the century, Lord Sheffield in his "Observations on the Commerce of the American States," writing in the early days of Cort's process, shows that it would help to make British iron as cheap as the foreign, an event which he considered would be more advantageous to England than the possession of her American colonies. Black died in 1799, Cort survived till 1800, so that as the eighteenth century closed, the most eminent scientific man and the foremost practical metallurgist of the generation stood side by side. To Cort we owe the greatest technical advance the modern world had seen; to Black the recognition of the importance of molecular energy in relation to metallurgical problems.

The production of pig-iron in this country also received a great stimulus from the discovery by Mushet about the year 1800, that the large
1800. deposits of blackband ironstone could be utilised. The century opened with, in round numbers, an annual production of pig-iron not exceeding 200,000 tons, of which less than one-third was converted into bars and other descriptions of wrought iron. The capital invested was under five millions, and employment was furnished for nearly 200,000 people.

Returning to the scientific aspect disclosed at the dawn of the century, the year 1803 was an eventful one for science. Nevertheless the
1803. impulse given to research was not in the most favourable direction for the advancement of metallurgic art. The influence

of a small proportion of carbon on iron had been recognised, but the quantitative relation between the iron and the carbon was only considered as bearing on the nature of the product, and not at all from the point of view of chemical union. When, therefore, in 1803, Claude Louis Berthollet published his *Essai de Statique Chimique*, it appeared that the action, of what for the moment I may be permitted to classify as the action of *traces* upon *masses*, was in a fair way to be elucidated for the following reason. Berthollet pointed out that "in comparing the action of bodies on each other which depends on their affinities and mutual proportions, the influence of mass has to be considered." Unfortunately in succeeding years the views of Prout, the courteous opponent of Berthollet, prevailed, mainly through the powerful aid of Dalton, who published also in 1803 his first table of atomic weights. Hence the phenomena which could not be attributed to fixed atomic proportions were set aside and usually neglected. Evidently the action of one-tenth per cent. of carbon on iron could not be explained by the aid of combining weights. The century was more than half over before a school of eminent chemists arose, who did not insist that matter is minutely granular, but in all cases of change of state made calculations on the basis of work done, viewing internal energy as a quantity which should reappear when the system returns to its initial state.

The production of cast iron and bar iron was rapidly increasing, and the suitability of cast iron and bar iron for the construction of
1802-7. bridges became evident to engineers, among whom Telford was pre-eminent. A distinguished professor, a worker in pure science, came, in the person of Dr. Thomas Young, to the aid of the technical worker. The need of studying the mechanical properties of iron and steel was evident, and Young showed that the work done in permanently extending or in compressing iron or steel could be represented by a coefficient, to which he gave the name of the "Modulus of Elasticity." This coefficient has probably rendered more service in the development of the study of the strength of iron and steel than any other which has been determined. It is of great importance, because upon it depends the deflection which a structure will take under strain. Young, evidently with a view to bring home evidence as to the great rigidity of steel, gives in his original paper a quaint illustration. He therein shows that if "Hook's law holds" a hanging rod of steel would have to be 1,500 miles long in order that the upper portions of it might be stretched to twice their original length. I would incidentally point out that on the basis of Young's calculation, such a column 1,500 miles high, if it were 1 foot $2\frac{4}{10}$ inches in diameter, would represent the output for the past year of Bessemer steel in this country alone. Statements of this kind had such a singular fascination for Sir Henry, that I have permitted myself a brief departure from chronological order in offering a new one.

In the year 1817 the patent was granted to the Rev. Robert Stirling, the specifications of which showed that he had a clear conception
1817. of the "regenerative principle," which, applied to furnaces, as will be shown later, has been so fruitful in connection with the manufacture of steel.

In the year 1818, Samuel Baldwin Rogers substituted "iron bottoms" for the sand ones which had been introduced by Cort in the puddling
1818. furnace. I find in the work on "Iron Metallurgy" by Rogers, published in 1857 (but apparently embodying much information he had promulgated in 1818), the statement that his "principal aim" in proposing the use of iron bottoms for puddling-furnaces was "to work the iron in a bath of cinder." He also suggested the use of a flux of a very basic character, and he adds the interesting statement that the use of "the proposed flux will rapidly remove the metalloids from the iron." He pointed out that "the metalloids were removed in the shape of oxides, and combined with the cinder in the puddling furnace." The actual result was to greatly improve the quality of British iron, and, therefore, Rogers deserves recognition, which has hardly been accorded to him, as a pioneer of the great basic process of dephosphorisation.

Between the years 1800-4 the amount of foreign iron annually imported was 40,200 tons, and one consequence of the improved method of puddling was to greatly diminish the importations, which in the period 1823 to 1830 fell to 17,015 tons a year.

In the year 1820 malleable iron began to replace wood for the manufacture of colliery rails, mainly through the efforts of Birkenshaw.

1820. The first quarter of the century did not draw to an uneventful close, for Faraday, working with Stodart, an eminently practical man, gave (in 1820) a stimulus to the study of alloys, and produced the first specimen of nickel steel. In a letter to De la Rive, dated April 20, 1820, Faraday writes:—"Mr. Stodart and myself have been engaged in a long series of experiments and trials on steel, with the hope of improving it, and I think we shall in some degree succeed." Later on he writes:—"If you knew the labour of the experiments you would applaud us for our perseverance at least."

In the year 1822 Faraday pointed to a fundamental difference
1822. between hard and soft steel, the latter yielding a "carburet of iron" when treated with hydrochloric acid, while hardened steel dissolves completely.

Early in the second quarter of the century notable progress was made, for on the 3rd of March, 1828, James Beaumont Neilson enrolled his
1828. patent for the application of the hot blast to furnaces. It has been suggested by two of my predecessors in this chair that the introduction of the hot blast might be characterised as a "lucky hit." Viewing, however, the merits of Neilson's great invention in relation to general metallurgical progress, it will be evident that exception may be taken to this suggestion. Neilson's contemporary, David Mushet, held that the introduction of the hot blast "marked one of the grandest epochs in the history of the manufacture of iron," and he urged that the discovery was the more remarkable as being opposed to received opinions and prejudices, "it being universally held that the blast should be kept as cold as possible." Neilson was an enthusiastic student in Anderson's College, Glasgow, and his strenuous advocacy of technical instruction proved him to be singularly in advance of his age; he was also an ardent experimenter. Moreover, he clearly says he was led to think that "if air was increased in volume by heat, it might be enabled to do more duty." In a sense he was right, for the expansion of the air, though perhaps

it was not so important as he thought, represents one-third of the energy contributed by the intervention of the hot-blast stove. That his invention owed anything to "luck" was evidently not the opinion of our own Royal Society, of which body he was elected a Fellow in 1846, as the discoverer of the "hot-blast system of manufacturing iron," and as being "distinguished for his acquaintance with the science of mechanical philosophy." The practical results of the hot blast were marked, and in the ten years which followed the introduction of his invention the production of pig-iron in this country was more than doubled. The history of the period is singularly interesting.

1842. Nasmyth's patent of June 9, 1842, embodies the first drawing of the perfected single-acting steam-hammer. Such hammers had been proposed by James Watt in 1784, and sketched by Deverell in nearly its present form in 1806.

1843-48. At this time a great investigator appeared in the person of Dr. Thomas Andrews of Belfast, the application of whose great work on the heat of combination will be referred to later.

1846. It is perhaps natural that in the rest of the first half of the century the most noteworthy feature seems to be the renewed attention devoted to the investigation of the nature of oxidation and reduction. As the investigations which were of great importance, were mainly conducted on the Continent, I must reluctantly leave their consideration until a future meeting. In the blast furnace there was evidently a kind of tidal ebb and flow in the relations of carbon and of oxygen, resulting sometimes in reduction, and at others in oxidation or carburisation; but the changes were all capable of more or less simple expression if viewed either from the atomic or the dynamic standpoint. As the furnaces grew in dimensions, their flaming tops threw a lurid glare over the country, and, "like the dying sunset kindled through a cleft," revealed the magnitude of the problems involved in blast-furnace practice, which were seen to be disproportionate to their apparent simplicity.

As regards the study of the nature of the ascending gaseous column, I may anticipate the remarks I shall have to make next year by pointing out that the labours of the illustrious chemist Bunsen were shared by the late Lord Playfair, and that a joint communication of theirs was published in the Report of the British Association for the year 1846.

In the first half of the century efforts were directed mainly to obtaining a material—cast iron containing some 3½ per cent. of carbon, and fusible at a temperature readily attained in the blast furnace. In the second half of the century, while efforts to obtain this fusible material were increased, attention was also directed to removing the carbon, and obtaining a product which had a melting point of 400° C. (720° F.) higher than cast iron. This product was either cast directly into ingot moulds or recarburised to the extent necessary to constitute the various gradations of steel. Sheffield hardly knew steel except as a material to be used for the manufacture of cutlery, for which she had been famous since the time of Chaucer.

It is characteristic of our British methods that special circumstances and needs, mainly arising in connection with the development of the steam-engine and railways, revealed the broad principles by which the production of iron must be governed. It was natural, therefore, as time went on, that

in the work of successive inventors the guidance of scientific principles became progressively evident as ill-directed efforts were gradually replaced by the results of systematic experiments.

The second half of the century began with an event of strange importance; for in 1851 the Great Exhibition revealed our industrial strength to all nations. The official reporter of the metallurgical group states that 2,250,000 tons of pig-iron were annually produced in this country, and that its estimated value was £5,400,000. The annual production had risen in fifty years from 200,000 tons to over 2,250,000 tons. Sheffield produced at the opening of the century 35,000 tons of steel, of which 18,000 tons were cast steel. Messrs. Turton exhibited a single ingot of steel weighing 2,688 lbs., but Krupp showed an ingot of double the weight, for our country was only preparing for the great change which was so soon to enable it to lead the steel manufacture of the world.

1850-51.

A noteworthy feature of the Exhibition was the collection of iron ores of this country exhibited by Mr. Blackwell, who subsequently, and most generously, provided funds for their analysis. With reference to this collection, the reporter points out that in this country "the ores are not carried far, except where there is great facility for transport." This is noteworthy, as before the century was much older an important supply of ore was brought from Spain, and in the near future we may even seek a supply for British furnaces from distant parts of our own Empire.

The year 1851 was, moreover, an important one for metallurgy in this country, as it saw, by the wisdom of H.R.H. the Prince Consort, the establishment of an institution which developed into the Royal School of Mines. If the projected scheme of instruction had been fully carried out, the provision of a general system of technical instruction, which the pressure of necessity is slowly forcing upon us, would have been anticipated by forty years.

In the year of the Great Exhibition the blast furnaces seldom exceeded 50 feet in height, and it was not until 1864 that Mr. John Vaughan erected a furnace 75 feet high, with remarkable results as regards increased output; since then the gigantic furnaces of the Cleveland district have become common.

The year 1856 will be ever memorable in the metallurgical annals of our nation as that in which Bessemer gave the description of his process to the world at the Cheltenham meeting of the British Association. As regards the process itself, we have too lately lost our great countryman, and many of us are too familiar with the details of his labours to be able either to fully estimate its value or to realise the wonder of its results. Let us try to think of the Bessemer process as I believe those at the end of the twentieth century will, whose views must range over a wider perspective than we can command. The economic aspect of the question will naturally strike the metallurgists of the twentieth century. They will see that in 1855 the make of steel in Great Britain did not exceed 50,000 tons, and the cost of the steel produced sometimes reached £75 a ton. They will see that thirty years after the publication of Bessemer's patent the production of Bessemer steel rose to 1,570,000 tons, and that ship plates were sold at £6 10s. a ton. It will be noted that before the century closed, the maximum production of Bessemer steel in this country in one year reached 2,140,000 tons. The scientific aspect of the process will, however, excite their widespread

1856.

interest, for before the end of the twentieth century, metallurgy will be taught in our older universities. It will be seen that, notwithstanding the title of Bessemer's Cheltenham paper, he recognised and insisted on the fact that the intense heat was engendered by the combustion of the elements within the fluid bath. It will be noted in what close relation the purely scientific work of Thomas Andrews, of Belfast, on the heat of combination, stands to that of Bessemer, and that another instance is presented of the dependence of industrial work on pure investigation. Bessemer's proposal to employ a mixture of steam and air will not be ridiculed as it has been, for speculation will be rife as to whether he did not hope that the liberated hydrogen might remove sulphur and phosphorus, notwithstanding the feebly exothermic result of the ensuing combination, and in spite of the cooling effect of water vapour. In view of the fact that endothermic combinations take place at a high temperature, the possible action of hydrogen as a decarburiser will be dealt upon. Prof. Noel Hartley's papers upon the Thermochemistry of the Bessemer process will be read with much interest. Surprise will, however, be widely felt that physicists generally of the last half of the nineteenth century did not see in the lovely flames of lilac, amethyst, gold, and russet, or in the "stars suspended in a flying sphere of turbulent light" which come from the converter, an appeal to fully investigate their cause and to study the dynamic problems presented by the intense heat engendered. Why was not the destination ascertained of 1,000 cubic feet of argon which accompanies the air passing through the metal during an ordinary Bessemer 10-ton blow? Why were not more strenuous efforts made to ascertain the effect of the temperature of the bath on the nature of the metal? Was not an attempt made to ascertain whether the iron itself, and any of the known elements it contained, were truly decomposed by the intense heat?

It will be felt that, as the eighteenth century had closed with a clear statement as to the true nature of oxidation, the nineteenth century had seen its magnificent application in the Bessemer process.

As regards the work of Mushet, future generations will, I believe, desire to add nothing to the words of the President of this Institution who, in 1875, had the pleasure of awarding the Bessemer Medal to him. Mr. Menelaus then said "that the application of spiegeleisen . . . was one of the most elegant as it certainly was one of the most useful inventions ever made in the whole history of metallurgy."

Attention must now be directed to the great process for the production of steel which involved the use of the "open hearth."

Sir William Siemens' life was one long and ultimately brilliantly successful effort to apply the kinetic theory of gases and the dynamical theory of heat to industrial practice. He was eminently a practical worker; but the depth and accuracy of his scientific knowledge gives him a place near that of all the great atomists from the time of Lucretius to that of our own countrymen, Graham, Joule, Clerk Maxwell, and Kelvin. In many of Siemens' papers, theory and practice are closely blended. In viewing the results of his labours, it will be seen in future ages that confidence in the trustworthy character of steel was finally established by experiments on metal produced in the regenerative furnace of Siemens. Looking back, it is astonishing with what difficulties the use of steel for structural purposes was beset. In 1859 Sir John Hawkshaw was not permitted by the regulations of the Board

of Trade to employ steel in the construction of the Charing Cross bridge. Time will not permit me to indicate the efforts which were made to induce the Board of Trade to remove the serious hindrances to the use of steel, which had "rendered the construction of the projected bridge over the Firth of Forth practically impossible." These efforts were not successful until 1877, when a committee, consisting of Sir John Hawkshaw, Colonel Yolland, and Mr. W. H. Barlow, were able to recommend that the employment of steel in engineering structures should be authorised by the Board of Trade. The steel employed was to be "cast steel, or steel made by some process of fusion, subsequently rolled or hammered"; one condition of such recommendation being that "the greatest load which can be brought upon the bridge of structure, added to the weight of the superstructure, should not produce a greater strain in any part than 6½ tons per square inch."

As regards the use of steel for shipbuilding purposes, in the year 1875, Sir Nathaniel Barnaby asked, "What are our prospects of obtaining a material which we can use without such delicate manipulation, and so much fear and trembling?" He partly answered his own question four years later, when he quoted experimental evidence as to "the recent successes" of open-hearth steel. In 1890 he completed the case by pointing out that naval architects now "have a perfectly regular material, stronger and more ductile than iron," and he speaks of "our lasting debt of gratitude for the birth and training of that true prince, William Siemens." It is hardly necessary to point out that the country owes the excellent materials used in naval architecture mainly to the productions of the regenerative furnace.

In connection with the production of mild steel, the addition of ferro-manganese to the decarburised bath proved to be most effective. We can hardly over-estimate our indebtedness to those whose perseverance ensured the adoption of mild steel for maritime and other purposes. "Looked at from the standpoint of to-day, when thousands of tons of such steel are made weekly without serious anxiety or trouble, it is scarcely possible to realise the anxieties and difficulties of the days when the manufacture of open-hearth steel was being perfected." To no one is our debt greater than to our Vice-President, Mr. James Riley, who bore a large share of the anxieties of the early days, and whose words are those I have just quoted.

With regard to the great modifications which have been effected in the Bessemer and open-hearth processes, reference must be made to that ample source of information, our Journal. It must also be consulted for the history of the appliances for heating the blast with which the names of Cowper and of Whitwell will always be specially connected.

In speaking of Bessemer and Siemens I have been obliged to depart somewhat from strict chronological order. I must now resume it at the year 1865.

1865. Sir Joseph Whitworth patented on November 24, 1865, a process for submitting liquid steel to heavy pressure, at the critical juncture when the metal is passing from the fluid to the semi-fluid state, to prevent any part of the casting from becoming hollow or unsound.

1866. In the year 1866 Graham's first paper on the occlusion of gases by metals was published in the *Philosophical Transactions*. Its results have been far-reaching, and will always rank with the metallurgical triumphs of the century.

In the year 1869 our Institute was founded. In view of certain aspects of the treatment which inventors had previously received from their

1869. industrial brethren and from the country, it will be evident that the time for its formation had fully come. Taking instances almost at random, I may remind you that Dud Dudley was, as he says, "with law suits and riots wearied and disabled" in the seventeenth century, and that Henry Cort was neglected and oppressed in the eighteenth. The great invention of iron bottoms in the puddling-furnace made by Rogers was received with ridicule, and he died in poverty. Popular tradition of Sheffield indicates that possession was obtained of Huntsman's secret "by the heartless trick of a rival." Neilson, though he warmly acknowledges the support he received from certain ironmasters, was treated with singular meanness by others. Heath fought single-handed for fifteen years "against a common purse, the accumulation of the wealth which he had created." Even Bessemer's early statements were received with incredulity and contempt. With the formation of our Institute all this is changed: men place the results of their work and experience freely at the disposal of their brethren, and each fresh advance meets with appreciative consideration. "Vigorous moderateness," wrote the late Walter Bagehot, "is the rule of a polity which works by discussion. . . . It was government by discussion that broke the bond of ages and set free the originality of mankind."

The history of our industry since the formation of this Institute is epitomised by the labours of those who have hitherto occupied the

1869-71. Presidential chair. The Duke of Devonshire, K.G., our first President, worthily sustained the honour of the name of Cavendish, one of the most illustrious in the scientific annals of our country, and the connection of the Duke with the iron industry at Barrow is an incident of the first importance in our industrial records. He highly appreciated the importance of science in relation to the progress of the nation; and the Report of the Royal Commission on Scientific Instruction, of which he was President, contributed in no small degree to the awakening of public attention to the subject. His noble foundation of the Cavendish Laboratory at the University of Cambridge stimulated research on the lines closely connected with this Institute, as the work of Clerk Maxwell, of Rayleigh, of J. J. Thomson, of Ewing, and of Heycock and Neville, abundantly testify. It is certain that the main efforts of his life were directed to developing the resources and improving the condition of the people. Neither rank, wealth, nor intellectual gifts had power to afiect the simplicity of his character or to lessen the deep sense of duty which controlled all his actions.

The life-work of our second President, Sir Henry Bessemer, has already been dealt with, and the lesson it teaches is how vastly important

1871-73. the labours of one man may be to a nation. In these days the facilities for work are much greater than they were, and results are obtained by an army of workers; but, as Stanley Jevons has pointed out, the influence of the individual genius is "not withering, but is growing with the extent of the material resources which are at his command." It was during the Presidency of Sir H. Bessemer that Snelus patented the use of basic lining for furnaces and crucibles, which was ultimately found to be so important in relation to the elimination of phosphorus from pig-iron.

Sir Lowthian Bell embodies for us the progress in blast-furnace practice of at least the last half-century. It was under his Presidency
1873-75. that the first Continental meeting was held, the place chosen being Liége, Belgium's great metallurgical centre. He was the author of the first paper communicated to the Institute, choosing as a subject "The Development of Heat and its Appropriation in the Blast Furnace." There is a passage in the Presidential address of Dr. Percy with reference to the work of Sir Lowthian Bell which I may be permitted to quote. Dr. Percy said: "His laborious, careful, and original investigations of scientific problems of the highest interest in the metallurgy of iron and steel must be so well known to this audience that any comment upon them from me would be superfluous, if not presumptuous." If Dr. Percy, the metallurgical historian of the age, thus shrank in 1885 from the attempt to give adequate expression to the value of Sir Lowthian's work, it would be impertinent in me to say more than that the fourteen years which have passed since Dr. Percy wrote, have only served to bring into greater prominence Sir Lowthian's unswerving devotion to the solution of those problems he has so patiently studied.

Attempts to improve the ancient operation of puddling by the aid of mechanical appliances, received their fullest development under
1875-77. the guidance of William Menelaus. The great usefulness of his career may perhaps be well indicated by the statement that he was among the first to be convinced of the vast superiority of steel to puddled iron, and urged its adoption with singular foresight and vigour. His position as manager of Dowlais Works gave great force to his advocacy. By lending his great mechanical resources and power of organisation to scientific research, he brought about some of the greatest improvements that were ever effected in the iron and steel industries. He associated himself, moreover, with Edward Riley, who, as an analytical chemist, subsequently made a distinguished name.

The work of Sir William Siemens has already been dealt with as fully as time will permit. I will, therefore, only quote the public
1877-79. tribute to his memory which was offered at the time of his death in 1883: "The nation at large has lost a faithful servant, chief among those who live only to better the life of their fellow-men by subduing the forces of Nature to their use. Looking back along the line of England's scientific worthies, there are few who have served the people better than this, her adopted son—few, if any, whose life's record will show so long a list of useful labours."

Edward Williams shares with Menelaus the unique distinction of having been the first to appreciate the great importance of Bessemer's
1879-81. discovery, and within three days after the publication of Bessemer's paper at the British Association he erected at the Dowlais Works a small fixed converter, had blown pig-iron, and had rolled the product into bars, "to the great astonishment of all concerned." His vigorous address as President of this Institute was remarkable for the then prophetic expression of belief, that the day was "at hand when either by a Bessemer converter or by the open-hearth . . . there will be produced with absolute certainty, with comparatively light labour, and (he hoped) with fair profit to all concerned, every kind,

variation, and quality of the metal iron which we rudely designate steel and wrought iron." He also made a striking appeal to educated intellectual young men who "hung listlessly" about the professions "to break through the absurd old prejudice against seemingly rough work, and come over to the healthy business of iron and steel-making, in which they might render the world good service."

1881-83. Josiah Timmis Smith, in his Presidential address, gave a remarkable retrospect of the period which had elapsed since the foundation of the Institute. He showed that, comparing the year 1880 with the year 1869, 2,250,000 more tons of iron had been made with the same amount of fuel, or we had, in fact, economised our fuel supplies to the extent of 10,000,000 tons. He gave a masterly summary of the progress in our industries, and eloquently pleaded that chemistry had proved its claims to be regarded as the hand-maid of the iron manufacturer, and had given our metallurgical art a place in relation to the exact sciences which it could never otherwise have occupied. He also urged with great force that our Institute had broken down the spirit of exclusiveness and prejudice, that is usually the most rampant where knowledge is most wanting.

1883-85. To Sir Bernhard Samuelson is due the credit of being the first to succeed in convincing the House of Commons of the national importance of Technical Education in its widest sense, and to induce it to grant a Select Committee to inquire into the provisions for giving instruction in theoretical and applied science to the industrial classes. I wish I knew which of his wise and careful utterances he would like me to quote. Left to my own choice, I reject reference to his elaborate array of statistics, and select the following brief passage from his Presidential address: "It is to the further development of the world's railways that we must mainly look in the future as in the past for the support of our trade." Bearing in mind what is happening in Egypt, in South Africa, in China, and on the frontiers of our Indian Empire, the vast importance of railways, to which Sir Bernhard refers, cannot be doubted. Hence the engineer, considered as a pioneer, is absolutely dependent for steel rails and for the material for the construction of bridges on the metallurgist, whose work is the real foundation of progress. One other sentence, which is typical of the whole tenor of his life's work, may be quoted: "It is in the mutual co-operation (in a scientific spirit) of every grade in our great craft that we may build up the hope, nay, that we may cherish the certain expectation, of placing it on even a higher eminence than that which it has already attained."

1885-87. In no other branch of modern scientific literature than that of metallurgy does one individual stand far above his contemporaries and absolutely dominate his subject as does Dr. John Percy. It may be fairly claimed that he did this, for he truly represents the progress of metallurgical literature during the nineteenth century. He was also the century's greatest teacher; he found metallurgy practised in this country as an empirical art. His splendid works contain a record of its progress; his lectures at the Royal School of Mines secured it a scientific basis, and he trained a body of workers in whose hands the immediate future of metallurgy still, to a great extent, rests. To few men does the nation owe more than to our President of

1885-87. The educational work Dr. Percy began is being actively developed. As regards its progress in the future—which is of vital importance—there seem to me to be no requirements that may not be abundantly met by the extension of existing institutions. The establishment of a Board of Mining and Metallurgy in connection with the new Teaching University for London, would, I am satisfied, greatly stimulate instruction in these subjects.

1887-89. Daniel Adamson will be known rather as a mechanical engineer, and the originator of the Manchester Ship Canal, than as a metallurgist. His Presidency of this Institute is, however, remarkable for his strenuous advocacy of the use, not only of steel as distinguished from iron, but that for definite purposes steel of a definite degree of carburisation and suitable composition should be employed. He also eloquently urged that the steel at all stages of its manufacture in its varied applications should receive suitable thermal treatment. He strongly advocated the use of steel for the manufacture of boilers, and he pointed out that by the use of steel rails and weldless solid rolled steel tires the saving to railway shareholders amounted to about £3,120,000 sterling per annum, while the safety and security of the travelling public had been correspondingly increased. No better indication of progress in the decade ending 1889 could well be given than this.

1889-91. The vast advance during the century in the applications of iron and steel in the manufacture of machinery, and more especially to locomotives, is fittingly represented by Sir James Kitson. We, moreover, owe him a deep debt of gratitude for the admirable way in which he represented the Institute by presiding at the autumn meeting which was held in Paris in 1889, as well as during the arduous but most remarkable visit to the United States in 1890. Sir James, by his unflagging vigour and unfailing tact, did much to cement the friendship of workers in iron and steel both among our neighbours in France and our kinsmen in America. I will only add that he has persistently advocated the use, and has well maintained the reputation, of that admirable material, "best Yorkshire iron."

1891-93. One of the most noteworthy events in the metallurgical progress of this country was the acceptance by Sir Frederick Abel of the post of Chemist to the War Department. The teaching of such illustrious men as Berzelius, Heinrich Rose, and Liebig was just in process of thorough application in this country when Abel left our matchless teacher Hofmann to take his place among the earliest trained analytical chemists whose aid was sought by the ironmaster. He thus became, as it were, the "Patron" of works chemists. They are men on whose patient, monotonous, and often inadequately recompensed, labours the quality of British iron and steel has in no small measure depended, and I am glad to have this opportunity for offering my brethren, the chemists in works, a respectful tribute of admiration. The magnitude of their work may be gathered from the fact stated in the Journal of our Institute that in one basic steel works over 110,000 determinations are made in a single year by three chemists and six assistants. Of Sir Frederick's numerous investigations, the one which appeals to us most closely is that which definitely settled, as Fe_3C, the composition of carbide of iron.

Lord Herbert of Lea, who was several times Secretary for War, and was

in office soon after Sir Frederick was appointed to Woolwich, appears to have been advised that "steel was wholly inapplicable for the manufacture of ordnance." When we consider what the nature of our present war material is, and reflect how large a part Abel played in its introduction and adoption, it will be evident that any further comments of mine as to the value of his labours would be unnecessary. He is himself a most active exponent of the truth "that the intimate blending of science with practice lies at the root of all industrial progress and success."

1893-95. I am quoting from an American source the testimony that "an historical sketch of the perfecting of modern processes of steel manufacture would afford the best glimpse that could be given of the career of Edward Windsor Richards." He was among the first to appreciate the need for reversing mill engines, and an early one erected by him is still at work at Ebbw Vale. He designed the works of Messrs. Bolckow, Vaughan & Co. at Middlesbrough, the largest in the kingdom, and as general manager of the famous Low Moor Works has fully maintained its reputation for the production of one of the most famous varieties of iron in the world. His connection with what is known as the basic process will be alluded to later on. In view of the fact that appliances will handle and forging presses deal with weights of steel up to 100 tons, he long ago anticipated the possibility of making 10 tons of steel into one ingot.

1895-97. The progress of an industry during the century can only be adequately indicated by the evidence afforded by statistics. In this respect no more comprehensive statements could have been desired than those embodied in the Presidential address of Sir David Dale. Sir David has, however, secured a firmer claim to the gratitude of the nation than that which is derived from his powers as a statistician. He has from time to time been the trusted arbitrator between masters and men, and as chairman of one section of the Labour Commission (1891-94), rendered admirable services in the interests both of capital and labour. He was also the representative of this country at the Berlin Labour Congress of 1890. His work has, moreover, enabled us to trace in the last twenty years of the century, the progress of the spirit of equity among all sorts and conditions of men, who have gladly borne testimony alike to his firmness and his justice. His efforts have been unwearyingly directed to removing difficulties which have from time to time arisen between employers and the employed. I need hardly allude to his long services as Treasurer of this Institute, nor do you need to be reminded that we owe the ability to carry on our work efficiently to his careful husbanding of our resources.

1897-99. To the foresight of Edward Pritchard Martin we owe the adoption in practice of one of the great processes which will render the nineteenth century memorable. I refer to what is collectively called the "Basic process." It would be impossible to trace its history now. I prefer in any reference which must of necessity be so brief, to appeal to the appreciative words in the paper which Sidney Thomas and Percy Gilchrist communicated to our Institute n 1879. They then stated that, "on laying some of the first results obtained from this six-pound converter before Mr. Martin of Blaenavon,

he at once recognised their importance, and from that time we have been deeply indebted to him for his unfailing and consistent support and much valuable advice and assistance." It need only be added that the metallurgical world is also under a lasting debt of gratitude to Mr. Martin. Later on other aid was as gracefully recognised. Mr. Thomas said, on the occasion of his receiving the Bessemer Medal (1883), "the present position of dephosphorisation has only been rendered possible by the frank, generous, and unreserved co-operation of Mr. Windsor Richards, and of our earlier and consistent supporter Mr. Martin." All those I have named have received the Bessemer Medal. We lost Sidney Thomas far too soon. Mr. Snelus, to whose work I have already referred, and Mr. Gilchrist received the highest honour the scientific world has to bestow—the Fellowship of the Royal Society.

The introduction of labour-saving machinery in the great Dowlais Works, which Mr. Martin directs, marks an era in British metallurgy.

This concludes the list of those who have hitherto presided over this Institute, and it will have been evident that from time to time other interests than those connected with iron and steel have been represented by your Presidents. We were reminded of this fact when the Institute first met, now twenty-four years ago, at Manchester, where we are promised a delightful meeting again next autumn. The Bishop of that great city then welcomed us by a quotation from Virgil, which connects the age of iron with the age of gold. The passage runs thus :—

> "quo ferrea primum
> Desinet ac toto surget gens aurea mundo."

I regret that space will not permit me to consider the progress of the century as measured by the work of our Bessemer Medallists. I hope, however, as regards the labours of the foreign recipients of the honour, to deal with them next spring. The metallurgy of America is so closely interwoven with our own, that I must permit myself a brief reference to four men who stand out from the industrial ranks of our kinsmen. These are Alexander Lyman Holley, the Hon. Abram S. Hewitt, John Fritz, and Prof. Henry Marion Howe, all of whom are Bessemer Medallists.

I only once had the good fortune to see the winsome pioneer of the Bessemer process in America, "our dear Holley," if I may borrow and adopt the phrase used to me by one of the American members at Stockholm last autumn, with reference to one the charm of whose character was neither impaired by difficulty or by success. All Holley did for the Bessemer process is fully recorded in our Journal, and it is only necessary to state, that from the time the first charge was blown at the Troy Works in 1865, there have been produced in America over 61,000,000 tons of Bessemer steel.

It was in the works of the Hon. Abram S. Hewitt that the first Bessemer converter was installed, and Mr. Hewitt was also the first to build an open-hearth furnace in the United States.

Mr. John Fritz was one of the small band of leaders who so successfully developed the Bessemer process in the United States, and excited the admiration of the metallurgical world by large outputs from comparatively small installations. He also aided in designing one of the most important arsenals in the world, where the highest quality of open-hearth steel was produced.

Of the labours of my friend, Prof. Henry Marion Howe, it would be difficult to speak adequately. As an experimental investigator he has greatly added to our knowledge of the properties of iron and steel. In the field of literature he has left on record a monumental work which enables him to rank with Dr. Percy as the metallurgical historian of the Anglo-Saxon race.

It may help us to estimate the value of the labours of the four men whose names I have given if we remember that at the present time the United States export about a million tons of iron and steel a year, while twenty years ago they were not exporting any. We may fairly consider, therefore, their influence on the rapid development of the United States navy. It would seem that we, in this country, in the belief in our insular security, had somewhat neglected the art of naval warfare, until Admiral Mahan reminded us of what we had done in the past, and of our possible course in the future, in a series of writings which have done much to convince the two nations, England and America, "that they are in many ways one."

It is time to offer a collective statement of the achievements which have either been actually effected or are in immediate prospect.

There are blast furnaces which will produce 690 tons of pig-iron in twenty-four hours, with a consumption of little over 15·4 cwts. of coke per ton of iron. The gases from the blast furnaces are used not only as sources of heat, but directly in gas-engines.

There are Bessemer converters which can hold 50 tons of metal, and open-hearth furnaces which will also take 50 tons, while 100-ton furnaces are projected. The open-hearth furnaces are fed with 1 ton of material in a minute, by the aid of a large spoon worked by an electro-motor. There are gigantic "mixers," capable of holding 200 tons of pig-iron, in which, moreover, a certain amount of preliminary purification is effected.

Steel plates are rolled of over 300 [sq.] feet in area and 2 inches thick. There are girders which justify the belief of Sir Benjamin Baker, that a bridge connecting England and France could be built over the channel in half-mile spans. There are ship-plates which buckle up during a collision, but remain water-tight.

There are steel armour piercing shot which will penetrate a thickness of steel equivalent to over 37 inches of wrought iron. The points of the shot remain intact, although the striking velocities are nearly 2,800 feet a second. There are wires which will sustain a load of 170 tons per square inch without fracture. Hadfield, whose labours will, I trust, be continued far into the twentieth century, has given us manganese steel that will not soften by annealing; while Guillaume has studied the properties of certain nickel steels that will not expand by heat, and others that contract when heated and expand when cooled. Nickel, chromium, titanium, and tungsten are freely used alloyed with iron, and the use of vanadium, uranium, molybdenum, and even glucinium, is suggested. There are steel rails which will remain in use seventeen years, and only lose 5 lbs. per yard, though 50,500,000 tons of traffic have passed over them.

Huge ingots are placed in soaking pits and forged direct by 120-ton hammers, or pressed into shape by 14,000-ton presses. With such machinery the name of our late Member of Council, Benjamin Walker, will always be connected.

There are steel castings for parts of ships that weigh over 35 tons. We

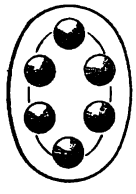
electrically rivet and electrically anneal hardened ship-plates that could not otherwise be drilled. Photomicrography, originated by Sorby in 1864, now enables us to study the pathology of steel, and to suggest remedial measures for its treatment. Stead's work in this field is already recognised as classical. Ewing and Rosenhain have, in a beautiful research, recognised quite recently by its aid, that the plasticity of a metal is due to "slip" along the cleavage planes of crystals. Osmond also, as an incident in a magnificent series of researches, shows that the entire structure of certain alloys may be changed by heating to so low a temperature as 225° C.

Passing to questions bearing upon molecular activity, we are still confronted with the marvel that a few tenths per cent. of carbon is the main factor in determining the properties of steel. We are, therefore, still repeating the question, "How does the carbon act?" which was raised by Bergman at the end of the eighteenth century. Nevertheless, from the molecular point of view, much may be said in answer to the question. The mystery is in fact lessened now, as it is known that the mode of existence of carbon in iron follows the laws of ordinary saline solutions. Our knowledge is, however, of very recent origin, and we owe mainly to the Alloys Research Committee of the Institution of Mechanical Engineers the development of Matthiessen's view that there is absolute parallelism of the solution of salt in water and carbon in iron.

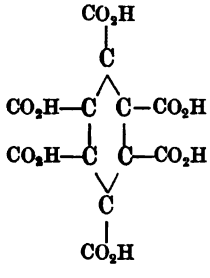
An ice-floe in a Polar sea contains a small percentage of salt; a red-hot ingot of mild steel holds some two-tenths per cent. of carbon, but both the carbon and the salt are in the state of *solid* solution. If the ice had been cooled below — 18° C., it would entangle a solidified portion of salt water, which was the last part of the mass to remain fluid. So in the steel ingot, when it has cooled to the ordinary temperature, there is a solidified "mother liquor" of carburised iron. We do not as yet know whether carbon is dissolved in fluid iron as carbon or as carbide. We do know, however, that the presence of 0·5 per cent. of carbon in iron (such an amount as might occur in a steel rail) lowers the melting point of the iron from 1,600° C. to 1,530° C. This lowering has enabled a calculation to be made, the result of which shows that the number of atoms in a molecule of carbon in *fluid* iron at this temperature is probably *two*. It can be shown that at a temperature of 800° C. the number of atoms in the molecule of carbon dissolved in *solid* iron is, in all probability, *three*. At lower temperatures the number of atoms is probably more than three. We metallurgists are not accustomed to think in atoms. Let me, therefore, represent such a three-atom molecule thus,  without assuming how much iron is associated with the carbon. Following Bergman's experimental method, but with the interval of more than a century separating his work from ours, we investigate the action of acids on carburised iron with a view to ascertain the nature of the atomic grouping of the carbon.

In explaining this, I may adopt the appended figure. It is most difficult even to attempt to make questions of atomic grouping clear in a paragraph, but the figure will be helpful. To the historian it suggests vivid pages of Italian history, as the six spheres so arranged constitute the arms of the

powerful family of Medici. To the chemist it is a precious symbol, and appeals to him as representing the carbon atoms as grouped in the benzene ring.



The result of treating carburised iron with various acids is the formation of marsh-gas and more complicated organic compounds, of which propylene, acetylene, ethylene, and naphtha may be mentioned. Does the nature of these products help us to ascertain the number of the atoms in the carbon molecule as it exists in cold steel? I have consulted organic chemists, among whom I would specially mention my colleague, Dr. Wynne, and their evidence is encouraging. The result of the action of powerful oxidising agents on certain forms of carbon is mellitic acid, $C_6(CO_2H)_6$, which is one of the benzene series,



and this favours the view that solid carbon contains twelve, or some multiple of twelve, atoms in the molecule. But mellitic acid is graphically represented in the annexed diagram, the carbon atoms being arranged as the six spheres are in the arms of the Medici. The group CO_2H is tacked on to each carbon sphere. From this it may be argued that the molecule of solid carbon consists of one or more carbon "rings." In cold steel the group of CO_2H may be replaced by the group Fe_3, which is broken off by the action of suitable solvents leaving free carbon. Hence the six-atom carbon molecule may exist in steel.

My object is merely to show you how far at the end of the century we have advanced in our knowledge of the mode of action of carbon, and I trust it will be evident that the progress is remarkable. We know that even in solid iron the carbon atom must push and thrust with great vigour, for we can measure the "osmotic pressure" the carbon atom exerts, and, as has just been shown, we can even picture the mode of the atomic grouping in the molecule.

I can only just sum up the evidence as to the occurrence of molecular change in iron. To Gore, and to Barrett, we owe the investigation of the nature of a fact not unknown to smiths, that iron on cooling from a bright red heat suddenly emits a glow. We now know that as steel cools down there may be at least six points at which molecular change occurs, accompanied by evolution of heat.

In a series of classical papers of which we are justly proud, for many of them have been communicated to this Institute, our member, Osmond, has shown what is the significance of these points, and has won an enduring reputation. We measure and record them photographically as readily as if they were barometric variations. It is known that six molecular changes occur in the purest electro-iron yet prepared, one of which is connected with the magnetic permeability of iron, while two points, which occur far below a red heat, appear to be due to the presence of hydrogen. In steel one point, at least, is due to the power iron has of dissolving carbon. Moreover, the molecular condition of steel cooled from an intense white heat is not the same as that of steel which has just been melted. To carry further the evidence as to the effect of an intense heat on iron in a vacuum is the task I have in prospect during my Presidency of the Institute. I may, however, express

my agreement with Lockyer's view that the evidence afforded by the atmosphere of the stars shows that our terrestrial iron is a very complex form of matter.

We must not lose sight of those relations of carbon and iron which involve physical equilibrium. Even the astonishing associations of iron and carbonic oxide in the volatile gaseous compound with which the distinguished name of Mond is connected, affords a triumph of dynamic chemistry. It is generally supposed that ozone is dissociated at 160° C., but Dewar has devised a beautiful experiment to prove that ozone has two centres of stability, and one of these is near the melting point of platinum. It seems to be the same with the relation of hydrogen and iron. We have recently learned that iron and hydrogen appear to be completely dissociated at 800° C., and yet the same iron heated to some higher temperature, say 1,200° C., will still yield hydrogen.

Let us suppose that Black, Cort, and Bergman were with us again, and had reviewed the present state of our knowledge and the work accomplished in the century. Let us also suppose that they could go to Sheffield and see an armour-plate rolled and finished for service, and then, visiting our Institute, hear the best explanation we could offer of all the incidental phenomena they had witnessed. Which would they consider the more advanced, our practice or our theory? They would probably hesitate to tell us, but would offer warm congratulations on the immediate prospect of the establishment of a National Physical Laboratory, in which investigations as to the properties of iron and steel will be continued.

Economic Considerations.

The relations subsisting between capital and labour are of vast importance to our industry, and it would not be justifiable to omit reference to them. There is, indeed, abundant precedent for the discussion of this subject in the Presidential addresses of Mr. Windsor Richards and Sir David Dale.

I venture to hope that the next generation will look back with astonishment to the deplorable aspects presented by what is known as the labour question at the close of the nineteenth century. It is only natural that British enterprise should be met by foreign competition, and I will not dwell on the evidence of our shortcomings in adapting ourselves to the requirements of foreign trade afforded by "our shaming Consular Reports." They are serious enough, but as regards the workmen, their demands for increased wages and reduced hours of work, and, what is far more serious, for the right to determine how little shall be done in those hours, entirely ignore the conditions under which other nations are competing with us. The situation last year was even perilous, for twelve unfinished warships bear eloquent testimony "to the great, though fortunately not irretrievable, misfortunes primarily traceable to the recent engineering dispute."

The multiplied strikes of the last few years have deprived the country of the great advantage it formerly possessed, both as regards excellence of work and punctuality of delivery. To take only the last coal strike; the indictment against the men was thus tersely expressed in *The Times*: "The men lost some £3,000,000 in wages; they crippled the coal trade; they stopped the naval manœuvres; they spread misery broadcast in the district; and they played into the hands of the non-associated owners, who realised

large profits, of which but a very small portion found its way into the pockets of the workmen." Capital and labour, which ought to be in amicable association, are too often antagonistic. It may be urged that the antagonism is but a struggle, and that the fittest and strongest must survive, and that we are powerless in the presence of the working of a natural law. Formerly some of us might have been disposed to accept this as inevitable. But my late distinguished colleague, Huxley, in the Romanes Lecture delivered by him at Oxford in 1893, recognised that there are two opposing methods at work in the government of the world. These are respectively the *ethical* and the *cosmic*. The practice of that which is ethically best involves a course of conduct which in all respects is opposed to that which leads to success in the cosmic struggle for existence. "In place of ruthless self-assertion, it demands self-restraint; in place of thrusting aside or treading down all competition, it requires that the individual shall not merely respect, but shall help his fellows; its influence is directed not so much to the survival of the fittest, as to the fitting of as many as possible to survive." Thus Huxley, one of the most acute thinkers of the century, has placed sympathy on a scientific basis by suggesting to us that, in the complex problems which the labour question presents, the ethical method must not be lost sight of; no effort to provide for the well-being of the industrial population can be too persistently adopted. Strangely enough in giving advice to workmen at this critical time, when, as the result of labour conflicts, trade has been lost to the country, we can appeal directly to their self-interest, and in this case industrial influences will be more effective than ethical ones. It is, moreover, through economic means and industrial influences that mankind tends to grow together, and it may confidently be anticipated that the workmen's self-interest, if only it can be rightly directed, will effect the changes in the relation between capital and labour which the moral sense of the men has been unable to accomplish. The highest ethical teaching of true leaders like David Dale, "will then find their late echo in the assent of the multitude."

"Within the trade union movement," write Mr. and Mrs. Sidney Webb in their very interesting work on "The Industrial Democracy," "we find the collectivist-minded working-man grounding his regulation of the conditions of employment upon what we have called the doctrine of a living wage." What that wage should be is most difficult to define; but is there an employer who hears me who is not anxious that each of his people should earn a "living wage," or who feels that the conditions of the life of labourers in the Black Country, as pictured by Charles Dickens in the forties, disgraced humanity? How could people who dwelt under such conditions respect themselves?

How can the legitimate self-interests of the workmen be rightly directed? We must hope that the inclusion of the teaching of economic subjects in the scheme of primary education will do much. We must hope that Boards of arbitration and conciliation will have immediate effect, and will find their full fruition with the rising generation, who may be expected to be more firmly disciplined and to have a higher sense of duty than their fathers. We must trust that frequent discussions between employers and the employed will enable mutual interests to be clearly seen. We must learn that the warmest sympathy with the workmen's rights is not inconsistent, in face of common dangers, with stern and vigorous treatment of labour difficulties which threaten the national prosperity.

Let us hope that advantage will be taken of the prevailing prosperity to place these questions on a satisfactory basis.

Conclusion.

It will have been evident how great a share our country has had in forming the age of steel. The range of properties steel possesses is wide, and by its use the energies of a multitude of workers have been, as it were, concentrated in a few great efforts which have exerted vast influence on the progress of humanity. Men with most varied aims have, by the use of steel, been enabled to reveal their genius. Especially is this true of the Members of that great Institution of Civil Engineers, whose hospitality is so generously extended to us. The forces of Nature have been utilised through the intervention of machinery, which could not have been constructed if steel had not been known. By the adoption of steel, distance has been abridged, and it has been possible to express our national attributes of courage and endurance in concrete forms. You who produce steel have enabled the designer of the greatest fleet ever seen to claim that our nation has "become the shipbuilders of the world."

As a plastic material steel has served as a vehicle for embodying the imagination of the art worker. To the chemist and physicist steel presents complex problems for research, and affords boundless hope that further changes in its composition or treatment will enable new wonders to be wrought which will make the future a rich inheritance.

At the end of the century we are hoping that a Royal Charter will be granted to our Institute, the members of which have, as I have shown, done so much. That the well-being of the nation depends on its scientific and industrial progress, was recognised in the charter given to that centre of all scientific advance, the Royal Society, in 1662, by His Majesty King Charles II. In this charter the King said: "We have long and fully resolved with Ourself to extend not only the boundaries of the Empire, but also the very arts and sciences." The method by which this was to be effected had been suggested long before by the better-known words of another monarch, who wrote the proverb: "It is the glory of God to conceal a thing, but the honour of kings is to search out a matter." Industrial or scientific truths are hidden, but we have freedom of search by "actual experiment." The humblest investigators of the properties of iron and steel may, therefore, make the resolve of Charles II. and share the glory of Solomon; for, bringing our intellectual gifts into a closer union with our practical interests, and broadening the boundaries of the metallurgical art, will assuredly enable us to make better use of our existing possessions, and will lead to the extension of the Empire.

THE CONTRIBUTIONS MADE BY FRANCE TO THE PROGRESS OF THE METALLURGY OF IRON AND STEEL DURING THE NINETEENTH CENTURY.

PRESIDENTIAL ADDRESS TO THE IRON AND STEEL INSTITUTE, 1900.[1]

INTRODUCTION.

The following address was delivered in Paris on the 18th of September, 1900, and transmitting it in the closing days of the year to the pages of the Journal of our Institute, enables me to express my grateful thanks for the singularly appreciative reception accorded to it in France. This is in no small measure due to the grace of the beautiful prose in which my friend M. Osmond's translation rendered it. The address was written in the confident hope that the bonds which have long united the scientific and industrial workers of France and England would be rendered far more comprehensive than they are, if the peoples of our respective countries better understood the interdependence of their work and interests. The reception of the address shows that the view that permeates it only needed the most simple expression to ensure sympathetic response, and to reveal the widespread existence of similar views to those it embodies. The warmth of our greeting in France, and the personal kindness shown to our members, was quite in keeping with the magnificence of the receptions and entertainments provided for us. We felt at home at once, meeting as we did in the house of the *Société d'Encouragement pour l'Industrie Nationale*, which was placed at our disposal for the third time in our history as an Institute. We are specially grateful to M. Robert de Wendel, President of the Comité des Forges, a member of our Institute, who presided over the reception committee, which comprised many of the most eminent scientific and industrial men of France. I would also thank the Minister of Public Works, M. P. Baudin, who received us on behalf of the President of the Republic. We were grateful to M. Eugène Schneider, a member of our Institute, who received us in the Exhibition at the very interesting pavilion of Le Creusot Works. In connection with Le Creusot, I would specially express our thanks to M. Gustave Canet for many acts of kindness, and for the reception which, as President of the *Société des Ingénieurs Civils de France*, he gave me when, earlier in the year, I visited Paris as one of the representatives of our Council. I am able to add, with great satisfaction, that M. Canet is now an Honorary Member of our Institute. As regards the excursions, M. A. de Montgolfier, who is, I am glad to say, also an Honorary Member of our Institute, received us munificently at the St. Chamond Works, while M. Henri de Wendel, our Bessemer Medallist, entertained a party at his works at Hayange and at Joeuf. The President of the Municipal Council of Paris invited us to the Hôtel de Ville, and M. Grébauval's eloquent and appreciative words of welcome will be remembered as one of the noteworthy features of the meeting.

Colonel and Mrs. Jekyll's delightful reception at the English House in the *Rue des Nations* at the Exhibition reminded us how close Paris is to London.

[1] *Journ. of the Iron and Steel Inst.*, 1900, No. 2.

Not the least claim to our gratitude was earned by the generosity of Mr. Henry Chapman, who again placed his offices at our disposal; while the ability and indefatigable energy of M. Henri Vaslin, our Local Secretary for the meeting, contributed greatly to its success.

I would end this brief preface by recording an incident which occurred at the first of the memorable receptions offered to us. A gifted actress, Mdlle. Marguerite Deval, incidentally appealed to the honoured name of Madame de Staël. Her unexpected allusion encouraged me to quote at a banquet which followed Madame de Staël's beautiful words, "*on depose fleur à fleur la courronne de la vie.*" They, however, suggest the gradual fading of human vitality, while the garland of the life of the century is enduring, for it is of steel, and the flowers and leaves composing it were gathered and entwined by the workers of both our nations, who hand it on untarnished to those whom future Presidents will, I trust, represent both in England and in France.

Christmas, 1900.

THE ADDRESS.

"It is an age so full of light, that there is scarce a country or corner of Europe whose beams are not crossed and interchanged with others, but there is none under heaven abounding with more variety of learning, where the sciences may be more fitly wooed or more surely won, than in France." These lines, written by Laurence Sterne in his incomparably clever "Sentimental Journey," were printed in the year 1768, the year in which Lavoisier's genius gained him admission as "Adjoint" to the French Academy, while at the same time the metallurgist Jars became "Membre titulaire." Sterne's is a glowing tribute, but we feel its justice and gladly adopt it as our own.

In the spring of 1899 I reviewed our national progress throughout the century in relation to iron and steel, and expressed the hope that at a future time I might give a similar account of the work in other countries. Our Institute is international, and some fifty of our members are either French or live on French territory; and as this is the third time that the Institute as a body has been hospitably received in France, my address may well be offered as a tribute to her. On both the previous occasions of our visits to Paris, as on the present one, the Société d'Encouragment pour l'Industrie Nationale generously placed its house at our disposal. In 1878 we were received, in the absence of the illustrious chemist, M. J. B. Dumas, then President of the Society, by Prof. Gruner, and in 1889 by M. Gustav Eiffel and by M. Haton de la Goupillière. This year the President of the Société is M. Adolphe Carnot; this name, made illustrious by sons of France, who have filled the highest office in her army and in the State, will always be received with deep respect in England, and is imperishably connected with the advance of physical science. In my capacity of Professor at the Royal School of Mines, I am proud to claim M. Carnot as a colleague, and also M. Haton de la Goupillière, who again receives us; for I need not remind you that he presides over the École des Mines Institution, the distinguished professors of which have since its foundation advanced both industry and science. With these eminent professors representatives of the Comité des Forges have associated themselves, under the presidency of one who bears a most honoured name in metallurgy. M. Robert de Wendel is, moreover, one of our earliest members, and thus connects two institutions of ironmasters whose aims have so much in common, and whose efforts have always been directed to the advancement of the science and practice of the metallurgy of iron and steel. In 1878 Sir William Siemens, our President, dwelt in his brief address on the advantages France enjoys in her admirable system of scientific and technical instruction, while in 1889 Sir James Kitson, who presided over us, contented himself with a few graceful words of acknowledgment, and none could offer such words better than he. At the end of the century, I shall be expected to cover a wider range of observation, and to pass in review certain phases at least of the iron and steel industry. I may, however, say at once that the impression given by the most comprehensive view it is possible to take of it admits of concise expression in a brief statement. It is that the main characteristic of the metallurgical work of the century has shown the interdependence between minute quantities of matter and the masses of metal in which they are hidden. The century's work has, moreover, to

a great extent revealed the way in which the small quantities of added matter act, and it has been shown that they exert profound influences even in solid metals; the fact that certain varieties of steel are "solid solutions" is now accepted, and the recognition of molecular movements in solids has become familiar. In no branch of work has the outcome of such knowledge been more striking than in the one to which all of us here are, in different ways, devoted. Metallurgists have again and again shown that no dependence is to be placed on the once famous maxim of the Duc de la Rochefoucault that "ceux qui s'appliquent trop aux petites choses deviennent ordinairement incapables des grandes." The influence of the apparently little on the obviously great is recognised, and we say with Browning—

> "Well, sir, the old way's altered somewhat since,
> And the world wears another aspect now:
> . . . . . .
> The small becomes the dreadful and immense."

The result is remarkable. The metallurgist, by adding small amounts of matter to iron, has literally made it possible to change the aspect of the world. He has enabled such structural triumphs as the Eiffel Tower and the Forth Bridge to be designed and built: he has created the Age of Steel, and of this age the palaces we have come to see on the banks of the Seine are the exponent, both as regards their construction and their contents.

Throughout the century, our nations have worked in unison, and shared the industrial triumphs by which the civilisation of the world has immeasurably gained.

The bonds of literature and of science have, moreover, for centuries united France and England, and the sympathy subsisting between men of letters stimulated industrial advance. In the thirteenth century Roger Bacon graduated as Doctor at the University of Paris before returning to Oxford, where his life's work was done. In the fourteenth century Chaucer translated the "Roman de la Rose." The great Scotch scholar, George Buchanan, an exile at Bordeaux, had Montaigne as his pupil, and Shakespeare in the "Tempest" and "Hamlet" paraphrases sentences of Montaigne. In the seventeenth century Isaac Casaubon, coming as the guest of King James I., profoundly influenced English thought, and by reviving at Oxford the study of Aristotle, prepared the way for the advance of experimental science in our older universities. In the eighteenth century, Voltaire, meeting Benjamin Franklin in London, rejoices that he can speak his langauge. The Abbé Prévost translates "Pamela" and "Clarissa Harlow," and makes them known to French readers. Every page of the "Esprit des Lois" proves how much Montesquieu learnt from Englishmen, and especially, it may well be, from those living near his home at Bordeaux, among whom the father of our own great chemist, Black, was prominent. How much may not Black himself have owed to the kindly interest of Montesquieu in those early days on the banks of the Garonne? The literary union of the two countries was close, but the bonds of union in science were firmer and more enduring, as it is natural that they should have been, for the literary men discussed abstractions, the scientific men principles. The correspondence between Lavoisier and Black bears abundant testimony to the eagerness with which experimental results obtained in the respective countries were

discussed. Reference was made in my inaugural address in the spring of 1899 to Lavoisier's tribute to Black, and I may now quote one sentence from a letter of the great Edinburgh Professor to his illustrious colleague in France. It runs thus—"Si le pouvoir de l'habitude empêche quelques-uns des anciens chimistes d'approuver vos idées, les jeunes ne seront pas influencés par le meme pouvoir; ils se rangeront universellement de votre côté." This they did. Lavoisier welcomed our scientific men who visited France. How helpful to scientific progress must have been the month of October, 1774, which Priestley spent in Paris; how interesting the dinner at Lavoisier's house when Macquer, who was present, hinted to Priestley that *plomb rouge* was too literal a translation, and that *minium* was the substance Priestley really had in view. Black died in 1799, and this brings us to the beginning of the present century, now so rapidly drawing to its close. It opened with a brilliant school of chemists in France, and as the names are familiar to us, would I could give you pictures of the men themselves; but Molière warned us, at a time when such sketches in words were fashionable, that "les portraits sont difficiles et demandent un esprit profond."

I must, therefore, refer you to Sir Humphry Davy, to whom the Emperor Napoleon gave permission to visit France, though the two countries were at that time unfortunately not at peace. Davy's vigorous hand and clear insight enabled him in friendly appreciation to preserve for us a few precious sketches in words which may be trusted, and may well be recalled. Berthollet he paints as being "modest, frank, and candid," with "no airs and many graces," while Vauquelin suggested to him "the mien and bearing of the French chemists of another age." Guyton de Morveau, Bonaparte's Master of the Mint and Baron of the Empire, was eighty years of age at the time of Davy's visit, and he says little of him. Gay Lussac, whom he placed at "the head of the living chemists of France," impressed him as being "profound, with great activity of mind and great facility of manipulation." Davy occasionally expressed himself in verse, and communing with these great Frenchmen surely strengthened the conviction that found expression in lines of his which embody a metallurgical simile, and run as follows:—

> "If matter cannot be destroyed,
> The living mind can never die.
> If e'en creative when alloyed,
> How sure its immortality."

Gay Lussac, Thénard, Laurent, and Le Play were personally known to Dr. Percy, my predecessor in the chair at the Royal School of Mines. Of the two first-named he writes in 1864, "Both are in their graves, and both bequeathed to France a legacy of fame of which she may well be proud. . . . Laurent also is dead, Le Play survives." Of Le Play, may not we who have seen the glorious Exhibition of 1900 remember how much this great metallurgist did in organising the Exhibitions held in Paris in 1855 and in 1867, at the latter of which he was Commissaire Générale.

The names of two more illustrious Frenchmen to which I would refer in this introduction are those of men who were personally known to some of us, and they connect us directly with the past. These are Jean Baptiste Dumas and Henri Saint-Claire Deville. Dumas was born in the year 1800, and stands first among the chemists of the nineteenth century. When I first met him in 1870, he was Director of the Mint, and it would be difficult

to say whether his distinguished manner owed more to gravity or to benignity, outward signs of the qualities of his heart which at once inspired respect and affection. I ask you to join in my tribute to his memory mainly because he represents a grand feature in French science, the union of theory and practice. He illuminated every elaborate research he undertook with the penetration of an inventive genius, and yet turned again and again to the consideration of industrial problems. Recognising their vast importance to the nation, he founded the École Centrale des Arts et Manufactures, where M. Jordan was professor until his lamented death in the present year deprived us of a distinguished member. Among those who have gone the only other memory on which I will dwell is that of Henri Saint-Claire Deville. Reference will be made to his work later on, and beyond offering these few words of personal tribute, I will only add that no man ever had more devoted followers. I am proud to have been one of those who were admitted to the charming gatherings in the laboratory of this gentle master, a laboratory in which all sorts and conditions of men met together, and where, as Dumas said, "chacun se plaisait dans ce milieu sans pretention, ouvert à toutes les hardiesses, fermé à toutes les idées fausses."

As regards the future, judging from experience in the past, the alloys now in use will probably give place to others, and interest will be concentrated not so much on the metals of the nineteenth century as on the men who enabled so much to be done with them. Any information respecting our great leaders will, therefore, be eagerly sought for. You may, nevertheless, have wondered that in an address devoted to iron and steel I should have dwelt so long on these few names, but the earlier chemists of the nineteenth century, like those of the ninth, were often metallurgists. There was no sharp line between chemical science and the metallurgic art which needed recognition of what are now known to be fundamental principles before it could make progress. You may think it stranger still that I should offer even the slender evidence I have as to the literary union of France and England. My answer is, that the culture of a nation should advance with its industrial progress, and the claims of literature are far too often neglected in relation to those of science. The attributes of iron and steel have, moreover, occupied a prominent place in the literature of our countries. They inspired Ruskin's despondent statement in the "Crown of Wild Olive," that "we have at present in England only one art of any consequence—that is, iron-making," and he adds, with reference to the manufacture of armour-plate, "Do you think on those plates your courage and endurance are not written for ever, not merely with an iron pen, but on iron parchment?" I quoted this sentence to my friend Osmond, and he at once capped it by the lines of Ronsard, who wrote in the sixteenth century—

> ". . . Je veux au mond publier,
> D'une plume de fer sur un papier d'acier,"—

lines which we both claimed as a poetic anticipation of the allotropy of iron, the pen being of harder iron than the steel on which it wrote.

If further justification is demanded, I would plead, in these days when due allowance is made for the influence of environment, that this address was written in the Mint, in full view of the one building in London which,

more than any other, specially reminds us of France—t[illegible] William the Norman. The turret is before me in which I like [illegible] in the fourteenth century, the erratic pupil of Arnaud de V[illegible]ymond Lully, worked. French names, moreover, are in consta[illegible]ucting our daily operations of coinage. We in the Mint consult [illegible] tables calculated by Gay Lussac, and the "Traité des Essais" [illegible] whose other writings are still my text-books.

The new century was not three years old when com[illegible] of the utmost importance appeared in each of our respective cou[illegible]rance, in 1803, Claude Louis Berthollet published his brilliant "[illegible]atique Chimique," and in England, Dalton, in the same year, g[illegible] world his atomic hypothesis, which enabled chemistry to be bui[illegible] a new basis. From that time, in all countries, science has adva[illegible] or less on the lines laid down by these great thinkers; that is, [illegible]g ideas have either had reference to the *mass* of Berthollet or th[illegible] Dalton. We may follow these lines in recording the metallurgical histo[illegible] century, but it will be necessary to trace the industrial applicatio[illegible]ence by a third line, connected by links with each of the other lin[illegible] dividing the century into periods, it will be possible to follow the direc[illegible] at least to consider the relations, of these lines without confusion. Alo[illegible]rthollet's line may be ranged all the results which involve the action of ma[illegible]d cannot be attributed to fixed atomic proportions, while, on the oth[illegible]and, the course indicated by Dalton involves recognition of the atomic [illegible]stitution of matter.

It must never be forgotten that both our nations had alr[illegible]y turned to Sweden, where theory and practice were united, where the [illegible]eputation of the pure iron of Dannemora was worthy of the teaching of [illegible]psala. In the great university of that city, Bergman, by pointing to carburisation as the fundamental principle on which the metallurgy of iron rests, conferred a gift on science and on industry the value of which France was the first to recognise. The eighteenth century had still some years to run when Vandermond, Berthollet, and Monge showed the real bearing of Bergman's work in a report, published soon after his death, in which they bear tribute to him as a grand chemist whom the world had lost too soon. In 1806 we find a fundamental statement by Berthollet's countryman and courteous opponent, Proust, which is of singular interest to us. At that early date he describes cast iron as a solution of carbide of iron in iron. He cites it as a case of a compound united to an excess of one of its elements, and clearly anticipates the modern view that carburised irons are solidified solutions in words which are so interesting that they may be quoted at length. He writes: "Mais si nous continuons pour le moment de prendre le carbure de fer pour une combinaison réelle, ou conviendra que son existence ou sa dissolution dans les fontes, nous offre l'example d'une combinaison uni à l'excès de l'un de ces élémens." It was in France, moreover, that the evidence as to the carburisation of iron was completed by Clouet's fusion of iron and the diamond; and when, in 1815, Pepys in England, using electricity as a source of heat, removed the last shade of doubt as to the possible influence of furnace gas, the full importance of Clouet's experiment was revealed.

Then came the attack of three great problems—the explanation of the

"reduction of metallic oxides" and "oxidation" of metals, and questions connected with the specific heat of metals. These must be taken separately, although our knowledge respecting them was developed concurrently through a long series of years. One of Lavoisier's many claims to our gratitude consists in his having enabled oxidising as well as reducing actions to be clearly understood; hence it became possible to carburise and decarburise iron intelligently, and technology was no longer guided by empiricism, but by accurate knowledge. As regards reduction, Lavoisier had recognised that the action of carbon on a metallic oxide was a mutual one; and, as he said, this observation leads us universally to very important reflections on the use of carbon in the reduction of metals. About the year 1814 Foucroy and Vauquelin concisely summed up what was then known by the statement that the removal of oxygen from burnt metals by carbon gave the metals "a new existence." The further explanation of reduction we owe to the classical discussion between Le Play and Laurent, on the one hand, and Gay Lussac on the other, which in the end showed that the reduction of oxides may, according to the nature of the oxide and the conditions under which the operation is conducted, be effected either by carbon or by carbonic oxide.

So far the advance was made rather on the lines of Berthollet than that of Dalton; but in 1819 Dulong and Petit announced before the Academy of Sciences their celebrated law in these words: "Les atoms de tous les corps simples ont exactement la meme capacité pour la chaleur." This was widely acclaimed; it was a triumph from the point of view that matter has an atomic structure; it seemed, as has been finely said, that Dulong and Petit, by connecting the fundamental properties of ponderable matter with those of heat, an imponderable fluid or a force, seemed to give the old Greek atomism a modern and higher consecration. The century had, however, not run half its course before Regnault, by a masterly series of experiments, traced the conditions under which alone this law, and certain other laws, hold good. On the results of Regnault's experiments depend the correct appreciation of the efficiency of every engine, whether driven by steam, or, as at the end of the century, by "waste" gases of the blast furnace. At the beginning of the century 6 lbs. of coal per hour were required to produce one horse-power in a steam-engine; now one-fourth of the above amount is sufficient—a result to which Regnault has in no small measure contributed. We can realise what this means in these days of the still thriftless use of coal, the great source of our industrial wealth. His calculations are of service in connection with every method or process in which the use of gas or heated air is involved, whether it be the estimation of the calorific power of fuel or of the efficiency of the hot-blast stove. So entirely was the importance of Regnault's work recognised, that our elder sister, the Institution of Civil Engineers, voted, in the troubled days of 1848, a sum towards defraying the cost of his research;[1] but the honour of participation was denied to us, though the intention was greatly appreciated in France, and we must be content to remember that our Royal Society awarded Regnault the Copley Medal, the highest honour it has to bestow.

I will now turn to the industrial aspect of the metallurgical advance made in France in the first quarter of the century. When the century opened,

[1] See Appendix at the end of the Address.

the production of pig-iron in France and in Great Britain showed less disparity than in later years. In the year 1801 the 420 charcoal blast furnaces in France produced 112,000 tons of pig-iron, while the out-turn in our own country was only 200,000 tons. As regards the question of the utilisation of the waste gases of blast furnaces, which is now deriving great importance from their use in gas-engines, France took the lead. So far as I can ascertain, and Berthier is my authority, in the year 1811 Aubertot made a successful effort to utilise the waste gases of blast furnaces in his works, which were situated in the Department of Cher. With singular generosity he placed the information he possessed at the disposal of his brother ironmasters, retaining only for his own exclusive use the application of waste gases to the heating of cementation furnaces. It was not until much later that blast furnace gases were utilised in our own country, and Aubertot was certainly the pioneer. In 1814 England made an industrial offering to France by lending her James Jackson, of Birmingham, who at the invitation of the Minister Chaptal occupied a forge at Trablaine in the commune of Feugerolles, and, establishing a cementation furnace, made, by the year 1816, 100 tons of crucible steel. In France the manufacture of "natural" steel obtained by the refining process under Beaunier, and by puddling with the modifications introduced in England by S. B. Rogers, attained great perfection under De Gallois, who established in 1830 near to Saint-Chamond the first English forge on the Loire. De Gallois also set up blast furnaces, the precursor of which had been the blast furnace established in 1782 at Le Creusot by William Wilkinson. At Janon, near Terre-Noire, a new era for French blast furnaces was inaugurated in 1821, and in 1830 at Janon the waste gases from blast furnaces were used for heating the blast. This was a noteworthy step in advance, but in the use of waste gases from the blast furnace, France had, as has already been stated, taken the lead. In 1820 MM. Boiguer and Dufand at Fourchambault, and M. François de Wendel at Hayange, had built extensive works which served as models for others. I need not remind you that his distinguished successor, M. Henri de Wendel, is our Bessemer Medallist this year.

As an indication of the progress which French metallurgy had made, it may be added that in the Exhibition of 1834, MM. Jackson Frères, the sons of William Jackson, exhibited an ingot of cast steel weighing nearly half a ton. Seventeen years later, at our own Exhibition of 1851, our heaviest steel mass was only a ton and a quarter, though Krupp showed an ingot of double the weight.

The London Exhibition of 1851 fittingly begins the second half of the nineteenth century.

The first halting-place in physical work must be made at the splendid calorimetric researches conducted in the fifties by Favre and Silbermann, to whom and to Andrews, of Belfast, we are indebted for the most trustworthy work on this subject. Then came a glorious period of French science, which the work of Henri Saint-Claire Deville adorned. Had he left nothing else than his researches on Dissociation, he would have more than earned our homage in connection with the metallurgy of iron and steel. By bringing into line chemical dissociation and evaporation, and chemical decomposition and ebullition, the researches of Deville gave the views of Isaac Newton on chemical action, so long misunderstood, the most startling confirmation.

In France, the country of so many great metallurgists, the school of Deville has done admirable service, not only in developing his work, but in bringing the results of his labours and teaching within the range of practical men.

Every ironmaster now knows how important in the practice of the metallurgic art, and especially in connection with the blast furnace, are the incomplete chemical processes which tend to re-form the identical substances with which a given operation started. The result of such opposed processes is the state of chemical equilibrium in which both the original and the newly formed substances are present in definite proportions, which remain unaltered so long as the conditions, more especially as to temperature and pressure, remain unchanged. The discovery of such incomplete reactions is one of the splendid gifts of France to the world. Berthollet recorded their existence at the beginning of the century in the famous "Essai sur Statique Chimique," to which I have referred. Dumas was the first to announce with precision the fact that these limited and opposed reactions set up a condition of equilibrium, and Berthelot and Péan de Saint-Gilles in 1862 established their existence by accurate experiment. It was Henri Saint-Claire Deville who in 1864 realised their wide-spread dominance, and it was the members of the school of Deville who gave an impulse to the promulgation of their master's views. The names of the brilliant members of this school are well known. They are Debray, Troost and Hautefeuille, Isambert, Lemoine, Ditte, and Mouret. Other names might have been mentioned, but the one on which I would dwell is that of Henri Le Chatelier, who by the masterly and authoritative statements contained in his "Recherches Experimentales et Théoriques sur les Equilibres Chimiques," and by his studies in solution applied to salts and to alloys, has firmly established his place among the great physicists of France.

As regards one of the great processes of the century, the name of Sir Henry Bessemer suggests memories of close association with France. We claim his process as one of the greatest achievements in the annals of British metallurgy, and we recall with pleasure how much Bessemer owed to the encouragement received from the Emperor Napoleon III. The necessity for improving the quality of steel arose out of some experiments in gunnery which Bessemer made at Vincennes. As is well known, his process was given to the world in 1856, and the Paris Exhibition of 1867 showed how much progress had been made. It is to M. de Billy, a member of the metallurgical jury of that Exhibition, that we owe an elaborate and appreciative report, and he was among the first to recognise that the process was the most remarkable of modern metallurgy, for it certainly introduced a true revolution in industrial practice. The application of the Bessemer process to phosphoric iron, which enormously extended its usefulness, was, as is well known, effected in England by Thomas and Gilchrist. The pioneer work of Snelus, also, is too well known to need more than mention here. I would, however, remind you that a correct appreciation of the conditions under which dephosphorisation could be effected was not wanting in France, and in this connection the name of Gruner comes prominently to the front. He pointed, in 1875, to the efficacy of dolomite and bauxite bricks in retaining phosphoric acid, and, therefore, in purifying phosphoric pig-iron, and he seems to have had a clear prevision of the practical solution of the problem which was so soon to be effected by Thomas and Gilchrist in our own country.

Turning to the great rival of the Bessemer process, we clearly see in the efforts which have led to the use of the open-hearth furnace in the manufacture of steel that the union of our national efforts is again conspicuous. As regards the great principle of regeneration as applied to furnace work, we claim its inception by Robert Stirling in 1817. Its development affords the most brilliant instance of the application of science to industry which the latter half of the century has witnessed. It is in no small measure due to the efforts of the eminent French metallurgist, M. Le Chatelier, Inspecteur-Général des Mines, that the open-hearth furnace was introduced into France, and at his instance Sir W. Siemens granted a licence to the Société Boigues Rambourg et Cie. of Fourchambault. It was, however, in the hands of Messrs. Pierre and Emile Martin of Sireuil that the manufacture of steel passed beyond the experimental stage. They did not merely melt steel, but manufactured it on the lines indicated by Réaumur in 1722. Siemens himself worked with the "pig and iron ore" process, and his name is associated with that of Martin in the development of the "scrap" process. For the later results, I will only refer you to the magnificent exhibits in the French section of the Exhibition, where you will see triumphs which have elicited homage from the metallurgists of all nations. It is claimed that it was the great works of Firminy that showed the great part that the process was destined to play by demonstrating that steel of definite and very varied qualities could be obtained with certainty by its aid. There can be no doubt that the publications of Euverte, which were the results of numerous experiments made at the Terre-Noire works, greatly accelerated progress in the use of open-hearth metal.

This brings me to a stage at which we may briefly review the achievements of the modern leaders of our great industry. Metallurgy had, in fact, been gradually increasing her demands on scientific investigators, who were in turn attracted to her service, not merely by the splendid rewards she offered, but by the interest of the problems presented to them. Three periods, which for the purpose of description may be considered to be decennial, separated the Universal Exhibitions which were successively held in Paris in 1855, 1867, 1878, and 1889. The progress made in each of these respective periods has been indicated by the three words, "novelty," "quantity," and "quality." In attempting to characterise the progress revealed in the present Exhibition by a single expression corresponding to the above, I would choose the word "intensity." In 1855 the metallurgy of iron and steel was almost stationary. The time-honoured processes were known to be inadequate, and technical workers were eagerly seeking fresh guidance. Twelve years elapsed, and the results of new efforts were revealed in the Exhibition of 1867, to which the labours of Bessemer, Martin, Siemens, Cowper, Whitwell, and Armstrong contributed so much, and in such original ways, to the general advance.

This was essentially the period of novelty. Eleven years elapsed, the Exhibition of 1878 showed the extraordinary development the new processes had attained, and this was the period in which the quantity of the new products was so remarkable. Then came the period during which the quailty of material improved, and the metallurgical exhibits in the Paris Exhibition of 1889 made it abundantly evident that the quality of steel, which was originally considered to be a treacherous material, had attained a high point of

perfection. New properties were developed in steel by the addition of such elements as silicon, and more especially by the rarer metals, manganese, chromium, tungsten, and later nickel. The result was that varieties of steel possessing distinct qualities were adapted to a wide range of application. Some kinds of steel were characterised by extreme hardness, while others were very soft; some were magnetic, in others the magnetic permeability was low; some varieties would harden by rapid, and others by slow cooling; certain kinds would even contract when heated and expand when cooled. In all cases the importance of submitting the materials which possess such strange and novel qualities to suitable thermal treatment became evident. In this way the period between 1889 and 1900 is reached, and this period I have already characterised by the word "intensity." No process of marked novelty has been devised, though there have been modifications and developments of the existing processes, and the scale on which they are conducted has been greatly increased. The investigators have in many cases been the same as in the preceding decade, but there has been intensity of aim and concentration of effort in bringing physical methods, and the results of investigation in pure science generally, into line with industrial requirements. In effecting this our two countries have worked in unison. Progress has been made mainly in two directions:—

1st. The preparation of new alloys of iron.
2nd. The study of the properties of iron and its alloys.

Alloys of iron and chromium present a remarkable instance. Berthier prepared the first alloy of chromium and iron in 1820, and Boussingault also devoted some attention to them. Brustlein had manufactured these alloys in the works of Jacob Holtzer, since the year 1877; but the Exhibition of 1889 first made us familiar with rich alloys containing 84 per cent. of chromium. In 1900 we find Brustlein renewing his efforts, and we are glad to welcome him on the jury of the metallurgical class. Chrome steels have passed beyond the crucible stage, and are prepared on the open-hearth with 3 per cent. of chromium, as is also a triple alloy of iron, chromium, and nickel for use as armour-plate and in artillery. As regards our English efforts, we all know how much Hadfield has done in extending the use of iron and chromium alloys for projectiles. At about the same time that Berthier gave us the first alloy of iron and chromium, Faraday prepared the first specimen of an alloy of iron and nickel, the future of which has proved to be so great. In the year 1884 M. Marbeau of the Société Ferro-Nickel produced their first alloys either in Paris or at the works at Lizy-sur-Ourcq, while at the Paris Exhibition of 1889 the Société showed the first alloys of iron with varying proportions of nickel. The journal of our Institute for the year 1889 contains a paper by James Riley, "On the Alloys of Nickel and Steel," which will be familiar to all of us. In France, at Montataire and at Imphy, attempts were also made to prepare alloys of iron and nickel, while at Le Creusot in 1888 a systematic study was made by M. Werth of the alloys of nickel with iron and with steel, a study which he continued at Fourchambault and at Imphy, obtaining results of practical importance. The manufacture of nickel steel in the open-hearth furnace was undertaken at Le Creusot, and in 1900 trials made at Annapolis on an armour-plate manufactured by Messrs.

Schneider & Co. revealed the remarkable properties of the variety of nickel steel which contains 5 per cent. of nickel. Since that time the manufacture of nickel steel in France has, as the contents of the Exhibition abundantly prove, assumed much importance, a result which is mainly due to the work of M. Werth. In the past decade it may well be claimed, therefore, that the efforts to employ nickel steel have been intensified.

I have not referred in this brief summary to the other elements which are present simultaneously with nickel. I need only appeal to results shown in the present Exhibition as indicating the way in which efforts to apply nickel steel have been intensified.

As regards the alloys of iron and manganese, the English name of Josiah Marshal Heath will be familiar to you all. A French engineer, M. F. Valton, director of the Terre-Noire Steelworks, was, however, among the earliest to give an explanation of the part manganese played as a deoxidiser in the final stage of the Bessemer process. I need not remind you that in 1876 M. Gautier made an important communication to our Institute on ferro-manganese, the use of which greatly contributed to the success of the manufacture of steel in the open-hearth furnace, and in 1868 Siemens called attention to the peculiar action of manganese on steel, and pointed to the influence of silicon in enabling sound castings to be produced. In 1875 M. Pourcel undertook the manufacture of ferro-manganese in the blast furnace. In the same year M. Muss of the Châtillon Commentry Company, and M. Jordan of the Saint-Louis Works, also took the manufacture in hand. Progress in this direction was rapid in France, and we all know how much our late and deeply lamented member, M. Jordan, did for this great branch of manufacture. The magnificent exhibits of iron-manganese alloys in the present Exhibition testify to the increased importance of the work which M. Jordan so recently directed. In England ferro-manganese was produced at the Pyle and Blaina Works, at Mostyn, at Darwin, at Wigan, and at the works of Messrs. Bolckow, Vaughan & Co. At the time of the former Exhibition in Paris, 1889, England was the dominant user.

I need not remind you that Hadfield, about the time of the former Exhibition in Paris, astonished the metallurgical world by producing steel containing from 7 to 21 per cent. of manganese, and possessing remarkable properties. His later work on the same alloys has only served to intensify interest in his earlier investigations, and it affords another instance of the renewed efforts which characterise the last decade. I will not weary you by passing in review the other alloys of iron, such as those with silicon, tungsten, and titanium; but I must not omit reference to the researches of MM. Moissan and Charpy on boron steel, of which we shall hope to hear much more in the future. May we not hope that in the next century vanadium, uranium, molybdenum, and even glucinum, will prove as faithful allies as certain of the better-known metals have been.

The second direction in which efforts have been intensified is in the study of the properties of iron and its alloys. The investigations may be conveniently divided thus:—

a. Those which relate to the physical properties of iron and its alloys, as revealed by thermal measurement.

b. Those which have for their object the study of the structure of iron, and the grouping of the constituents in its alloys as revealed by the microscope.

The work that may be ranged in both of these groups had an earlier origin than is quite realised at the present day. As regards pyrometry, which occupies a prominent place in the first group, space absolutely forbids my attempting to give a history of the blended efforts of our two countries, and I must only permit myself to recall a few of the more prominent names, and not pass beyond the limits of the present century. Guyton de Morveau in 1808 fully recognised the value of the early pyrometric efforts of Wedgwood. Magnificent work with the air thermometer has been done by Saint-Claire Deville and his school, and the work may be traced back to Princep and to the distinguished Frenchman, Pouillet. As regards the two methods which are now employed, the initiation of the use of thermo-couples is entirely French. The work began with Antoine Cæsar Becquerel, and was continued by Pouillet and by Edouard Becquerel. On the other hand, Siemens, in England, was the first to demonstrate the eminently practical nature of the pyrometric method, which depends on variations in electrical resistance, a method which was destined to be perfected and extended by Callendar and by Griffiths.

If, however, we turn again to France, we find Henri Le Chatelier completely changing all the details of pyrometric work that involved the use of thermo-couples, and his success is the more remarkable, as Regnault greatly discouraged experimenters by stating that he saw little that was hopeful in the prospect of the use of thermo-couples. Le Chatelier has thus conferred a debt of gratitude on industry which it will be difficult to adequately acknowledge. At the time of the Paris Exhibition of 1889 the value of the Le Chatelier pyrometer was beginning to be recognised by industrial workers; but the next step was made in England, when, in 1892, a recording pyrometer with a thermo-couple was first introduced into the Dowlais Works. It is now evident, as the result of efforts made in both countries, that all delicate operations, such as quenching steel gun-tubes and rolling armour-plate, and all operations in which changes of vital importance take place within a narrow range of temperature, must be controlled by careful pyrometric observations. I hope it will ultimately be seen that the work entrusted to me by the Alloys Research Committee of the Institution of Mechanical Engineers has shown our national co-operation with France in the solution of the great problems connected with the constitution and properties of steel.

The century opened with the expression of fundamental but comparatively simple views as to the constitution of steel. The importance of carburisation had been accepted and the protean nature of iron itself had been recognised in Bergman's classical phrase, "*polymorphum ferrum.*" As the century closes it is seen that iron has gathered to itself, often in considerable volume, numerous associates with which it was originally entrusted only in small quantities. Industry has consequently been enriched by varieties of metal possessing properties hitherto unknown. These properties have been investigated by a host of workers, and the mention of only a few names may seem to be invidious. Nevertheless, I am satisfied that when writers come to look

back to the end of this century, as we do to its beginning, the phenomena connected with iron and steel to which they will revert will be comprised in the words "points of transformation." Our country will receive its share of these retrospective thoughts, for the names of Gore and Barrett are way-marks. Tchernoff will be remembered, for he proposed a thermometric scale by which manufacture of steel could be controlled.

From among Frenchmen one name will arise in the memories of future historians of metallurgy, and that name will be Osmond. It will not be forgotten how much Osmond did in defining the modes of existence of carbon in steel. It will be remembered that by his observations a single point of recalescence became resolved into many points. He traced the influence of hysteresis, and showed how the position of the points of transformation vary, within a certain range of temperature, with the element with which the iron is allied. He showed that if a certain variety of steel has been quenched at a point above or below its critical point, it may present one or other of two states of equilibrium. These may be widely different, either as a consequence of change either in the allotropic state of one of the constituents or in the chemical grouping at the moment the metal passes the critical point. I am not unmindful that M. Grignon, who translated Bergman's "De Analysi Ferri" into French, shared his views as to the allotropy of iron, nor do I forget that Cizancourt pronounced advanced views on the subject in 1865, as did also Tait in the Rede Lecture delivered at Cambridge in 1873. Osmond, in fact, insisted on the allotropy of iron, proved its fundamental importance, and identified himself with its study, but that, though it is his great achievement, is far from being his only one. He showed that the properties of steel are a function of the cycle of temperatures to which it has been subjected. There have been many workers whose investigations possess strong individuality and significance peculiarly their own whose results nevertheless intensify the interest of Osmond's labours and conclusions. I hope I may be forgiven the brevity with which I cite these. Pionchon showed that at a temperature of 700° the specific heat of iron is altogether exceptional. Guillaume studied a series of nickel steels in which the transformations are reversible. This reversibility is associated with some important peculiarities as regards expansibility. Henri Le Chatelier pointed to magnetic irreversibility in the case of certain manganese steels. He, moreover, examined the influence of the gaseous atmosphere surrounding the steel in which the points of transformation occur. Charpy studied the hardening of steel with reference to the critical points. Tomlinson showed that the molecular change in iron is revealed by a change in magnetic properties. Madame Curie showed that the allotropic change effects a true magnetic transformation. Dumont recently pointed out that in nickel steel the point at which magnetic transformation occurs depends on the proportion of nickel present, while experiments by Guillaume and by Dumont indicate that chromium acts like carbon on certain irreversible varieties of steel and lowers the temperature at which magnetic transformation occurs. Carnot and Goutal isolate various compounds which in special varieties of steel give rise to variations of properties. The great importance of critical points in relation to the dimension of grain in steel, and consequently to its strength and extensibility, has been shown by Brinell, by Sauveur, and by Morse.

The second group into which modern investigation may be divided

involves the use of the microscope, and the application of this instrument to the metallurgy of iron is less recent than it is often supposed to be. Réaumur in 1722 describes the structure of a chilled casting under the microscope, and traces the changes in the structure of softened cast iron as modified by the elimination of impurities. Francois, again, so early as 1833, took the very interesting case of the direct reduction of iron from its ores, and followed the successive changes by the aid of the microscope. The following passage, translated from this quaint and accurate observer, is full of interest, and might almost have been written by any of us to-day :—

"If to these analytical data observations under the microscope with a magnification of 300 to 400 diameters be added, it is seen that ordinary iron is merely a metallic network with a close-grained tissue with submerged scoriaceous opaline, sometimes subcrystalline, portions, and with little globules and metallic grains ranged in every direction. Sometimes nests of translucent prismatic and bacillary crystals, with metallic portions adhering, are noticed hidden in the paste. These are the grains of steel which can be made to disappear by heating."

England in turn in 1864 gave a new impetus to this important branch of investigation by the labours of Sorby, in whose admirable work polished and etched sections were employed. The microscope as an implement of research hardly received due recognition until Osmond published a classical series of researches which have earned the lasting gratitude of investigators. In no branch of my subject do I so much regret that the limitations of space have obliged me to confine myself to the bounds of our two countries, as I should like to have dwelt on the micrographic work of Martens, Sauveur, Behrens, and many others. I will only add that the work of Stead deserves special recognition, not only for its minute accuracy, but for its originality. Quite recently Ewing and Rosenhain have obtained most interesting results, which go far to explain by micrographic evidence the elasticity and flow of metals, and also the mode by which crystals grow in metallic masses.

A Report of the Departmental Committee on Steel Rails recently issued is the first Government publication in England in which the importance of micrography has been recognised.

Scientific discoveries have during the century worked a complete change in our intellectual appreciation of natural phenomena, but in our work the standpoint of the new century will be singularly like that of the old. A few tenths per cent. of carbon hidden in iron still dominates our branch of metallurgy. Bergman recognised this before the nineteenth century began, and insisted both on the polymorphy of iron and the importance of carbon in relation to it. He pointed out, moreover, that in every great change effected in the constitution of iron, heat is either absorbed or evolved. The sentence in which Bergman sums up the results of his own calorimetric experiments is full of interest :—"Si præcedentis momenti allata experimenta considerantur, haud difficulter elucet, quemlibet statum respectu caloris absconditi circmscriptum esse."

Allotropy and carburisation of iron will be the first passwords of the twentieth century, and Osmond, the great allotropist of the age, has blended their significance by showing that the power iron has to retain carbon in solid solution depends on the particular allotropic form in which the iron exists. There is no other fact which so profoundly affects the industry of the world.

We now know, but only at the end of the century, that in steel of somewhat low carburisation, but wide industrial application, the heat equivalent of the allotropic change is exactly double that due to the change of the relation between the carbon and the iron, the respective figures being 18 and 9 calories.

As one of the last important engineering works in a century which the Eiffel Tower would alone have made remarkable, I may refer to the Alexander III. Bridge, a great structure in which a different material is used from that employed by M. Eiffel. It crosses the Seine in a single span, and 2,200 tons of cast steel have been employed in its construction. If the steel used in such a structure is heated to a temperature of 1,000° and is "quenched" by rapid cooling in air to about 600°, the metal so treated becomes stronger, more elastic, and resists shock better than if it had been annealed. Hence the material adopted in this great work of the very able engineers, MM. Résal and Alby, which so intimately expresses the genius of the Exhibition of 1900, affords the last cognate illustration of the importance and accuracy of Osmond's views.

I must not omit some reference, though it must necessarily be brief, to the metallurgical literature of our two countries. This has been greatly enriched by the admirable treatise on "Metallurgy" written by Dr. John Percy, which developed into a series of volumes, containing no less than 3,500 octavo pages, the last of the series appearing in 1880. He was, it will be remembered, President of this Institute during the years 1885-87. His volumes are remarkable throughout for minute accuracy, and for the care with which the illustrations were prepared, almost every woodcut being a trustworthy though small measurable drawing. He has given us, in terse and vigorous English, a priceless record of many early processes, and ones which, though later, are obsolete. He was firmly impressed with the fact that metallurgical problems demand for their investigation the exercise of the highest analytical skill, and involve considerations worthy of those who delight in transcendental inquiries. He effectively quotes Réaumur's remark, "L'utile bien considéré a toujours du curieux, et il est rare que le curieux bien suivi ne mène pas à l'utile." I have elsewhere observed that he studied in Paris, making the acquaintance of the leading French chemists of the time, who doubtless directed him towards the line of work to which his life was mainly devoted. Percy may fairly be said to have originated the English literature of metallurgy, for until his time the works on metallurgy were slender and far between. This was not the case in France, where the works of Rivot, the admirable and profusely illustrated treatises of Jordan, as well as those of the great chemists I have named earlier in this address, were well known. France, moreover, possessed in the *Annales des Mines* a veritable storehouse of knowledge, which has done for the iron and steel industries throughout the century what our own journal has attempted to do in the latter half of it. I would only add, that if Percy has been the historian of metallurgy, Gruner systematised it. I would gratefully offer my testimony to the value of his "Traité de Métallurgie" as a model of scientific exposition and methodical criticism which enabled the tangled threads of metallurgical practice to be unravelled. Few men have more effectively combated than he did the assumption of prejudice and mystery which all branches of the metallurgic art too long retained.

There are many subjects you will regret that I have not touched upon.

The question of naval defensive armour, for instance, might well have been referred to even on so eminently pacific an occasion as the last Exhibition of the century, but I will content myself with reminding you that France was the pioneer in the employment of naval armour, and that the launching of the armour-protected *La Gloire* in 1860 gave the signal for the reconstruction of European navies.

The extraordinary development of the use of iron for constructive purposes revealed by the present Exhibition, demands that some reference should be made to the relations of iron and steel to art, with which industry and science are so closely connected.

> "And trade is art, and art philosophy,
> In Paris,"

as Mrs. Browning reminded us. The vast array of ephemeral buildings which line the Seine has been compared collectively to a huge organism, the bones and fibres of which are of iron and steel, covered with an investing body of plaster that has served as a basis for adornment of all kinds. There are some who doubt whether, from an architectural point of view, the lavish use of the new resources which metallurgists have afforded has been successful. A subtle critic, M. Robert de la Sizeranne, in a brilliant paper recently published, entitled "L'Esthétique du Fer," takes a despondent view of the result, and considers this new use of iron to be "à la fois le triomphe du progrès scientifique et son châtiment." But when he turns to the beautiful bridge, which, as I have already said, is an exponent of the genius of the Exhibition, he writes enthusiastic words, which I may well quote, and are as follows:—"Nous ne quitterons pas les bords du fleuve sans avoir senti la vie. Car elle est dans ces formes admirables du pont Alexander III. Ceci aussi c'est de l'art."

For my own part, being a metallurgist, I cannot expect that any importance will be attached to my individual opinion on an æsthetic question, but I would venture to observe that ideas of beauty are instinctive, and that pleasure in the contemplation of any work, whether of nature or art, depends on delicate and untraceable perceptions of fitness, propriety, and relation. This being admitted, I find myself unable to stand under the Eiffel Tower, and follow the course of the curved lines, which suggest the details of an immense but delicate coral, without being carried away by the impression that the structure is not only wonderful but beautiful.

The part played in the industrial evolution of the world by iron and steel metallurgists will be evident to all. The fact that they have contributed with commensurate success to the advancement of pure science is less generally known, and I may well, therefore, devote a few words in conclusion to recording some instances which readily present themselves. The carburisation of iron offers the first case in which the diffusion of solids in solids was observed. The study by metallurgists of the associations of carbon and iron has elucidated the most complicated case yet known, and indeed the only one which has been worked out, of metallic solid solutions. It presents, moreover, a unique case of the importance of allotropy in connection with metals. In 1,000 parts of steel, 997 parts, more or less, may be iron and the rest carbon, but the result of the union is a metal that is more widely used and has more varied attributes than any other. It would seem that nature has enshrined in steel

a series of her most complex secrets which we must discover as a condition of our successful use of it. Metallurgists have carefully investigated, and conduct daily, operations of vast industrial importance, in which the presence of a third body enables either elementary bodies or compounds to react on each other. By habitually conducting operations at high temperatures, which often invert ordinary chemical reactions, the metallurgist has acquired a mass of information as to the reactions that do occur, and the compounds that are formed under such conditions. Pyrometric records have, moreover, enabled the equilibrium of the less fusible metals in their liquid as well as in their solid state to be studied—a branch of work which chemists generally have not been in a position to undertake. The necessity for submitting the physical and mechanical properties of iron and its alloys to rigorous tests, as a routine operation in works, has afforded a rich store of information as to the molecular constitution, not only of metals, but of matter generally. Metallurgists have to deal with cases in which a mass of metal is acted upon by added matter in proportions that are too minute to intervene directly by the formation of chemical compounds with the whole of the mass, while in some cases no compounds are formed. The influence of the atom must, therefore, be more or less directly exerted. Hence it is that we, who still conduct processes, the traditions of which came down to us from mythological times, have done our share in "giving the old Greek atomism a modern and a higher consecration."

We hold this meeting as the representatives of the greatest industry the world has seen. We are more than this, for we are the exponents of the scientific and industrial union which subsists between our nations, and of the national appreciation that has remained unabated though tumults have shaken our peoples. May both nations in the coming century not forget how much we owe to the old Greek guidance. The Greeks gave us the name Siderurgy, by which our art is known in France. Plato, moreover, told us that the god who moved men through their sympathies inspired the invention of all industrial art, "the melody of the Muses, the metallurgy of Hephæstus, the weaving of Athene;" and if you have followed this brief address, you will realise how much metallurgical progress has owed to sympathy—the great interpreter which joins the industrial workers of France and England in a bond of peace that is stronger than iron, truer than steel, and yet is one which is sufficiently extensible to embrace all our peoples.

Appendix.

The statement as to a vote in the troubled days of 1848 of a sum towards defraying the cost of Regnault's research was made on the authority of M. J. B. Dumas, who, in his charming *éloge* of Victor Regnault (*Discours et Eloges Académiques*. Paris: Gauthier Villars, tome ii., 1885), states that the Société des Ingénieurs de Londres, struck by the beauty of Regnault's results, wished to place at his disposal the necessary funds for the continuance of his experiments. He adds (p. 185): "On aime à rapeller ce vote libéral des ingénieurs anglais, constatant une fois de plus que la science appartient au mond civilisé et qu'elle ne connait pas de frontières." Dumas thus definitely alludes to a "vote"; but he was, as it proves, imperfectly acquainted with the circumstances, and I was unable to test the accuracy of his information

in time for the delivery of the Address. I have, however, by following an indication given me by my friend, Prof. Henri Le Chatelier, satisfied myself, though with great difficulty, as to the facts. It appears that what M. Dumas believed to be "ce vote libéral des ingénieurs anglais," was really a generous offer of an individual engineer, the late Mr. R. S. Newall, who wished Regnault to accept £500 "to enable him to complete his experiments on steam," as is recorded in a note in Mr. Newall's writing, which Mrs. Newall has most kindly shown me. The offer was not accepted, for the French Government supplied the necessary funds, and, as M. Dumas correctly states, "La France pourvut elle-meme à la continuation de l'œuvre commencée et que reste son œuvre." It has seemed to me to be in every way desirable that this interesting episode in international scientific history should be in all respects correctly described, hence the addition of this appendix.

"METALLURGY IN ITS RELATIONS TO ENGINEERING."

An abridgment of a "James Forrest" Lecture delivered by Roberts-Austen at the Institute of Civil Engineers on April 23rd, 1902. *This was his last public address.* ("*Proc. Inst. Civ. Eng.,*" vol. xix., p. 218.)

The Council has requested me to deal in this lecture with the relations which subsist between the metallurgist and the engineer; it must not, however, for a moment be imagined that the metallurgic art is not included in the wide range covered by the work of this Institution. It has from its earliest days earned the gratitude of members of my profession, and of miners as well as metallurgists, by discussing our papers at its meetings, by publishing them in the Proceedings, and by placing us as Honorary Members in the roll of the Institution, which contains the names of so many distinguished engineers who have done so much for the country and the Empire.

"If I were called upon," wrote Mr. G. P. Bidder[1] in 1860, "to define the object and scope of the profession of Civil Engineer, I should say that his particular province is to take up the results discovered by the abstract men of science, and to apply them practically for the commercial advantage of the world at large, and to diffuse their beneficent influences among all classes of his fellow-creatures." The metallurgist practising an industrial art has helped the engineer to do this, and in evidence I need quote no other testimony than that of Sir John Fowler, who wrote as follows in the presidential address he delivered in 1866:—"The profession has probably been assisted by the experiments and writings of its members and of distinguished men of science more in the material of iron than in any other substance." It is from iron and steel that my illustrations will be mainly borrowed.

It might at first be thought that the relations between metallurgists and engineers, which have become so intimate and enduring, arose quite simply from common interests. The metallurgist supplied materials which the engineer accepted for constructive purposes as being well suited to his needs, and co-operation might be supposed to have directly resulted from the recognition of the benefits that would arise from mutual service. The case is, however, far from being so simple as this. Communication between those who had extracted metals from their ores and adapted them for the use of the engineer, and those who actually employed the metals in construction, has seldom at the outset been quite direct. Again and again in industrial history the relations we are to consider have been strangely stimulated by the intervention of men who sometimes were neither engineers nor metallurgists, but devoted their lives to abstract science. They recognised the value of certain metals and alloys for definite uses, they investigated their mechanical properties and proclaimed their merits to engineers. The intervener then disappeared, leaving behind some coefficient or constant bearing his name by which he became gratefully remembered. Such cases are frequently met with in the older history of metallurgy and engineering, and they constantly occur now. Two typical cases will suffice. One of these may well be taken from the fifteenth century, when the metallurgist did

[1] Presidential Address, *Minutes of Proceedings Inst. C.E.*, vol. xix., p. 218.

little for the engineer, and so much for the art workman. At a glorious period of Italian art and science, the astronomer, Galileo, brought metallurgists and engineers together. A visit to the Arsenal at Venice led him to study the mechanical properties of metals, and by applying the laws of mechanics to the endurance of solids, he incidentally showed what good service metals might render. We do not associate the great Florentine with a testing laboratory; he nevertheless stated that copper wires, and consequently all cylinders of drawn copper, might be 4,801 brasses, or some 8,565 feet long, without breaking with their own weight.[1]

It is a long step from the fifteenth century to the nineteenth century, but Dr. Thomas Young adopted a similar illustration when he wished to convince engineers that certain varieties of steel could be trusted for definite purposes. It was the rigidity of steel that Young wished to demonstrate; he, therefore, between the years 1802 and 1807, gave us the very valuable constant that bears the name of "Young's Modulus." He pointed out that, if Hooke's law holds good, a hanging cylinder of steel would have to be 1,500 miles long in order that the upper portions of it might be stretched to twice their length, if that were possible without breaking the metal. It may be mentioned, parenthetically, that if such a cylinder 1,500 miles long were 1 foot $2\frac{4}{10}$ inches in diameter, it would represent a recent year's output of Bessemer steel in this country. It is the same story now; metallurgists who are working at the physical side of their art are presenting the engineer with metals and alloys which were undreamt of a century ago, and are inspiring confidence in their use.

It is not easy to fix the period in industrial history when the metallurgist began to render the engineer essential service. Suppose that in this country Stonehenge were taken as a starting point. It is certain that metallurgists cannot claim to have been useful to the early civil engineer-architect who designed that crowning example of neolithic art. The venerable and stately structure arose from the plain at a time when bronze tools were known, but were not in general use, and had not replaced the stone axes and hammers by which the huge monoliths were dressed.[2] Mr. W. Gowland considers that the transition from the stone to the bronze age in this country may be placed at about 2,000 years before our era.

In another phase of engineering work, we know that Rome, in the days of her occupation of this country, looked to the metallurgists of our island to supply the lead of which the pipes were made that fed the aqueducts and baths of the eternal city.[3] The Romans also used metal in building construction, as is pointed out by Rondelet in his "L'art de batir" (Introduction, vol. i.), who gives as instances the portico of the Pantheon and the baths of Antonino Caracalla. Evidence, again, of the labours of the metallurgist is supplied by the well-known wrought-iron column at Delhi, which has an inscription of the fourth century[4]; and again there are the thirteenth century iron girders and beams of the Orissa temples. Such magnificent

[1] This calculation would not agree with tests of modern wire of pure copper; it more nearly corresponds with cylinders of hammered copper.

[2] *The Times*, Dec. 20, 1901.

[3] "The Early Metallurgy of Silver and Lead." W. Gowland, F.S.A., Society of Antiquaries, 1901, p. 18.

[4] "Some Evidence as to the very Early Use of Iron." Sir John Vincent Day, Phil. Society, Glasgow, Dec. 4, 1872.

efforts as these were not maintained, and no widespread and continuous records of the metallurgists' contributions to early constructive work can be presented. On the other hand, the civil engineer advanced mechanical science and "directed the great sources of power in Nature for the use and convenience of man" for ages before the metallurgist rendered more than incidental assistance. The engineer availed himself of the wood and stone he found in a natural state, and the world has realised this, and has from very early days acknowledged a deep debt of gratitude for splendidly achieved aqueducts, bridges, and embankments which were executed by members of the great profession it is now my privilege to address. Time will only permit me to offer a few illustrations. No metal finds a place in the primitive bridges which in the middle ages crossed deep gorges and mountain torrents in Savoy. Another instance is afforded by the very interesting thirteenth century cantilever bridge taken from the drawing of Villars de Honnecourt [1]; it is made up of 20-foot wooden beams, which might have been much longer, and no metal enters into its construction. Or, to turn to the bascule bridge,[2] there were many examples so early as the fourteenth century, in which the only metal is the pivot and the rod of the locking-lever and the guide-rollers. As regards stone bridges, Ferrario describes the Ponte di Trezzo, which crossed the Adda in Northern Italy, and had a span of 237 feet and a rise of 68 feet. It was built by Bernabo Visconti about the year 1377, and was the largest stone arch known.[3] The great Tuscan painter, Leonardo da Vinci, 1452-1519, who is said to have invented the pound lock and the breech-loading gun, had to trust to wood and stone for the erection of those wonderful structures which have rendered his name famous as an engineer. If we turn to sixteenth century work, the Italian metallurgist, Vanoccio Biringuccio, or the German metallurgist, George Agricola, both wrote treatises, and the illustrations of the latter author show how small a part metals played in the engineering plant connected with the mining industry. In this way it would be possible to pass in review the centuries preceding the sixteenth without there being much to record until the output of cast iron became considerable. The first cannon in this country were cast at Bucksted in Sussex in 1543, and it is well to remember that England owed much of her supremacy to the iron guns cast in the reign of Queen Elizabeth.

In Europe the metallurgist did not give the engineer much substantial aid until the eighteenth century. In that century works in cast iron were very noteworthy; but I can only cite a few of them, such as the Coalbrook Dale bridge, erected in the year 1777, with a clear span of 100 feet. As I shall have but little more to say about cast iron, it may be remembered that a plan was submitted to Parliament by Telford and Douglas [4] for crossing the Thames by a single arch of cast iron, of 600-foot span, but the experiment was considered to be too hazardous, and metallurgists lost this magnificent chance of rendering service to engineers. The Albion Mills, constructed

[1] "Album de Villars de Honnecourt, Manuscrit publié en fac-simile," J. B. Lassus et A. Darcel, 1858, plate xxxviii.

[2] "Dictionnaire Raisonné de l'Architecture Français," par E. Viollet-le-Duc, vol. xvii., p. 255.

[3] Address by Sir B. Baker to Section G of the British Association. *Report*, 1885, p. 1188.

[4] An Encyclopædia of Civil Engineering, by E. Cresy, 1847, vol. i., p. 475.

by Rennie in 1784, and worked by Watt's steam-engines, are cited as the first example of the employment of iron in every part of machinery.[1]

In the Nineteenth Century, the metallurgist, as I hope to show, more than atoned for his somewhat tardy and intermittent efforts to supply materials for construction on an adequate scale. Viewing the century as a whole, it may be divided into three very unequal periods in relation to the production of iron and steel :—

I. For about two-thirds of the century cast iron and puddled iron were the main materials in use ; then

II. The age of steel began and gradually gained vigour, while

III. Towards the end of the century great attention was devoted to considerations connected with the molecular structure and molecular properties of steel, and to enforcing the action of carbon by the addition of various other elements, often in very small proportions.

Henry Cort patented his great process of puddling in 1784, and as the nineteenth century dawned its merits were fully recognised. It is hardly possible to imagine that a metallurgical history of the world could provide a theme about which more eloquent pages could be written than those which describe the history of Cort's invention. The interest centres in the three great men—Cort, the inventor ; Joseph Black, the chemist ; and James Watt, the illustrious engineer. Cort's story has often been told, but I think that the relations between the three men I have named are neither sufficiently well known nor remembered. Our industrial supremacy as a nation was the outcome of those relations which, briefly stated, were as follows :—Black discovered the latent heat of steam. Watt, by the improvement in the steam-engine, greatly facilitated the development of the blast furnace. It would be impossible to overrate the importance of this. It can be shown that the necessity for pumping water out of mines was the main factor in the evolution of the steam-engine ; and, in turn, the development of our national metallurgy of iron dates from the time when Watt's steam-engine enabled air to be readily pumped into the blast furnace. Cort, by the process of puddling, converted the product of the blast furnace into decarburised iron, which was in a sense a new material. It was the chemist Black who reported to the Government that the results of analyses, and of such mechanical tests as the period afforded, showed that puddled iron was more suitable than foreign iron, on which England had hitherto mainly depended for the manufacture of the appliance on which, as he said, the "lives of our seamen and the safety of our ships had depended." Let me quote the testimony of Fairbairn, who wrote as follows in 1865, at a time sufficiently remote from that at which Cort worked to enable his merits to be fully appreciated. He pointed out that this great metallurgist's inventions had "conferred an amount of wealth upon this country equivalent to six hundred millions sterling," and had during three or four generations "given employment to six hundred thousand of the working population of our land." It has been said that the history of many a great invention is one long martyrology. Cort's case is one of the saddest instances of this. His neglect by ironmasters and by the Government has recently been the subject of an eloquent appeal by Mr. Charles H. Morgan, who presided over the American Institution of

[1] Presidential Address by Sir John Rennie, *Minutes of Proceedings Inst. C.E.*, vol. v., p. 19.

Mechanical Engineers when this Institution offered its hospitality to American engineers in 1900. He said of Cort: "With one stride he stepped ahead of all competitors, scored a mark deep and lasting that will remain for ever upon the history of metallurgy and manufacture of iron as a magnificent landmark. It was his alone, and his reward has been practically nothing." I could only reply that Cort's name is emblazoned on the frieze of this room side by side with that of Watt and opposite the name of Newton, which bears eloquent testimony to the place he holds in the memory of engineers.

As regards the applications of wrought iron, I would only point out that the nineteenth century was but young when Robert Stephenson built his tubular bridge across the Menai Straits, which, as is well known, was 1,500 feet long, and one of its openings was no less than 460 feet. I must dwell no longer upon wrought iron, except to give the briefest reference to the ironwork of the great Exhibition of 1851, which gave us the "Exhibition girder," and to the "Great Eastern" steamship, an outcome of the genius of Brunel. As Sir John Wolfe Barry said in his Presidential Address, it is a lamentable thing that she should have been broken up for old iron. As the first half of the century was drawing to its close, I find that Sir W. Cubitt, F.R.S., in the address he delivered as President of this Institution in 1850, refers to the Report of a Commission appointed in 1847 for the purpose of inquiring into the conditions to be observed by engineers in the application of iron in structures exposed to violent concussions and vibrations. The Report contains the following words, which suggest unbounded confidence as to the products then supplied by metallurgists and to the ability of engineers who used them: "Considering that the attention of engineers has been sufficiently awakened to the necessity of providing a superabundant strength in railway structures, and also considering the great importance of leaving the genius of scientific men unfettered . . . any legislative enactments with respect to the forms and proportions employed would be highly inexpedient." We shall see later of what vital importance, in relation to newer materials than wrought iron, the question of small but rapidly-intermittent stresses has become.

I must proceed directly to the second period into which, for the purpose of this lecture, the past century was divided. This begins with the year 1856, when the Bessemer process burst upon an astonished metallurgical world, to be followed later by the Siemens-Martin, or open-hearth process. It is unnecessary that I should describe these splendid metallurgical triumphs. As regards the first of these, Sir H. Bessemer presented a memorable paper to this Institution in 1859. Steel produced by these two methods differed essentially in mechanical properties; but the important question is what reception could engineers accord to these new materials? They could only be expected to submit them to the methods of forging and annealing as they were then known, and judge them on their merits; and the results were in many cases very disappointing. The slowness with which confidence in steel was gained will appear remarkable, and the successive steps by which its reputation was established will be more rapidly gathered by a few quotations from addresses of Past-Presidents of the Institution than from any other sources. Sir John Hawkshaw, in 1862, seven years after the date of Bessemer's patent, wrote as follows:—"Should it turn out that steel, or homogeneous iron . . . uniform in quality, and of double the strength

of ordinary iron, can be manufactured in large quantities at a moderate price, and can be easily manipulated, . . . then some things which cannot now be done at all, will be rendered practicable." Sir John Fowler, in 1866, takes a more hopeful view. He writes thus in his Presidential Address: "With respect to steel . . . before we can safely adopt it to any considerable extent for purposes of construction, it will be necessary to have careful experiments similar to those of Mr. Eaton Hodgkinson on the resistance and crushing force of cast and wrought iron; but," he adds, "so promising a material as steel will amply repay all the trouble that may be bestowed upon it." In 1877, Sir Nathaniel Barnaby had asked, as regards the use of steel for shipbuilding purposes, "What are our prospects of obtaining a material which we can use without such delicate manipulation and so much fear and trembling?". In 1877, Sir Frederick Bramwell,[1] not in his Address to this Institution, for that was not delivered until 1885, but in a lecture given elsewhere, predicted the great future that steel *properly treated* was destined to play. In 1880, Mr. W. H. Barlow, F.R.S., alludes to the fact that the Cunard *Servia* and the Allan *Parisian* were built of Siemens-Martin steel; and he points out that for great bridges "the employment of steel becomes a necessity, because the weight required to make them of iron would render them impossible." Lord Armstrong, in 1882, states, in reference to the inner tube of a gun, "I have always used steel for that purpose when I could obtain it of suitable quality, which, in the early days of my experience," he adds, "was a difficult thing to accomplish." By the year 1887, the address of Sir George Bruce shows that the merits of steel had at last received due recognition. The address is full of glowing statements, as well it might be, for the crowning triumph of the age of steel—the Forth Bridge—had set the question of the case of steel at rest, and Sir George exultingly exclaimed, "At the Menai Bridge the total quantity of iron was 11,468 tons; at the Forth Bridge there will be 50,000 tons of iron and steel." Sir George concludes with the statement that in nothing is the effect of the use of steel more marked than in the railway interest throughout the world, for "steel rails, with a life far exceeding that of iron, are now produced at a price greatly below that at which iron rails were ever manufactured," and he points out that the use of mild steel for boilers had enabled a saving of 70 per cent. in the consumption of coal to be effected, and an increase of 110 per cent. in the speed of ships to be attained.

In 1895 Sir Benjamin Baker, in his Presidential Address[2] to this Institution, dwelt very fully on the apparently "mysterious" changes which take place when a steel rail cools down. In his Address, in 1885, as President of the Mechanical Section of the British Association, he called attention to the extreme importance of rapidly-intermitted strains on steel. He showed that a very moderate stress, alternating from tension to compression, if repeated with sufficient frequency, say 100 million times, would cause fracture (in a shaft) as surely as sharp bending to an angle, perhaps only ten times. No one has done more than he to insist on the importance of phenomena which practical engineers are constantly encountering and cannot explain, and reluctantly have to relegate to the class known as "mysterious," but when the engineer has overcome these mysteries, and

[1] *Proceedings of the Royal Institution*, 1877, p. 314.
[2] *Minutes of Proceedings Inst. C.E.*, vol. cxxiii., p. 1.

a Forth Bridge, or some other great structure, is successfully erected, we are forbidden to consider it as a work of "transcendent genius," but as a symbol of the forces behind its designer, who is to be regarded merely as an exponent of the age of steel. While fully admitting the debt that genius owes to its environment, is there not danger in the view that leads us to undervalue the influence of personality? Personality is the channel through which the world receives any contribution to the advance of human progress, even though it be so great a one as to give an age its title—the age of steel. There are some men who, besides being the exponents of their age, belong to all time, and surely such men shed light from within, and do not merely reflect it from without. I like to remember that Browning makes the chemist Paracelsus say that—

> "in man's self arise
> August anticipations, symbols, types
> Of a dim splendour ever on before
> In that eternal circle life pursues."

I must now come to the third period in the history of steel, which began towards the end of the past century—the period in which molecular structure and molecular properties of steel and other metals were studied.

The metallurgist must undoubtedly bear a large share of responsibility for the delay in recognising the most suitable methods of treating steel. It has been well said that "Where the physical explorer advances the engineer settler quickly follows."[1] The problems in the case of steel were, however, singularly complicated, and in the seventies the physical explorer had neither advanced far nor had obtained secure title to the territory. Now that the necessity of a National Physical Laboratory has been admitted in principle, and it has been proclaimed that the first work to be undertaken in it will be connected with steel and other alloys, the nation should not, as new varieties of steel or new alloys are discovered, suffer the untold loss which delay in investigating the properties of ordinary carbon steel has entailed.

What is it that metallurgists did when they gave the world mild steel? They provided iron containing, say, 0·2 per cent. of carbon, but that, on a small scale, had been known for centuries. They really gave a cinder-free solid solution of carbon in iron, a material the properties of which could be varied by the addition of other elements than carbon to the fluid bath and consequently to the solid solution which was produced by cooling the metal. Directly this was understood a field of wide extent was opened to the investigator. Let me, however, indicate the importance of such work by quoting the prophetic words of a Past-President of this Institution. Sir John Hawkshaw in 1862 wrote: "Men do not suddenly discover new worlds or invent new machines or find new metals . . . there is nothing worth having that has not been the result of 'combined and gradual' process of investigation. . . . Could we," he adds, "but hit upon an inexpensive mode of doubling the strength of iron, the advantages might be equal to those that would flow from the discovery of a new metal, more valuable than iron has hitherto been." The problem thus shadowed by Sir John Hawkshaw is being solved by metallurgists with regard to structural steel; they are "doubling" its strength by the aid of careful thermal treatment and by

[1] Sir B. Baker, Presidential Address Inst. C.E., *loc. cit.*

suitable additions of other elements than carbon. This result is not the outcome of random effort, but of patient investigation, the result of which has shown that steel is a solid solution of certain elements dissolved in iron. It is, moreover, a solid solution, the properties of which are profoundly modified by the presence of minute quantities of certain dissolved elements or substances, so that materials possessing a wonderful range of properties are presented to the engineer. [The nature of solid solutions was then discussed at some length with special reference to the carbon-iron diagram. This diagram has been referred to already in the section dealing with the Alloys Research Reports (pp. 132-153) and has been reproduced there (Plate XI.)].

In 1899 Mr. Osmond of Paris communicated [1] to this Institution the results of some remarkable experiments of his own on the alloys of iron and nickel. In the case of an alloy containing 24·5 per cent. of nickel, the critical point, which occurs in ordinary iron at 766° C., lowered to 40° C. and is not completed at the ordinary temperature. I have said that the alloy of iron with 25 per cent. of nickel is of great interest to engineers, and I will only add that Mr. Yarrow has pointed to its value in connection with the durability of water-tube boilers, and his conclusion [2] is as follows:—It is "not unreasonable to assume that nickel steel (20 to 25 per cent. nickel) boiler tubes will have, as regards acid corrosion, a vastly longer life than those of mild steel, and as regards deterioration from the action of heated gases or steam, at least twice the durability of mild steel." Surely this is very valuable evidence as to the importance of molecular variation. It would have been possible to demonstrate the same action in a simpler form. If steel containing some 1·5 per cent. of carbon be quenched in iced brine, it becomes comparatively feebly magnetic, and the substance produced has been called "austenite" by Mr. Osmond, who has shown that if this substance, austenite, be placed in liquid air and still further cooled it regains the power of magnetic permeability. In this case the quenching in iced brine preserved the β, or non-magnetic form of iron, to the ordinary temperature, and it required a further reduction of temperature by treatment with liquid air to produce ordinary or magnetic iron.

The question then arises, can we examine these mysterious actions at work and study their successive steps? First let me repeat that what has hitherto been considered a solid metal really behaves like a fluid. Our belief in the comparative solidity of lead was shaken when it was known that gold would diffuse itself into it with a considerable amount of freedom. Can we, from an examination of a solid metal, gain insight into its past molecular history? A page of Fénelon enables me to lead up to the means by which this may be effected. "There was no painter in the land of his imaginary travels, but the object to be copied was placed in front of water in basins, of gold or silver, and after a time the water froze and became a mirror on which an ineffaceable image remained." It is much the same with molten metals and alloys; when they become frozen or solid they retain in their mass, and often on their surfaces, impressions of the vibrations which have passed over them, and traces of their own internal molecular history which after suitable treatment the microscope will reveal. Many other illustrations

[1] *Minutes of Proceedings Inst. C.E.*, vol. cxxxviii., p. 312.
[2] *Transactions Institution of Naval Architects*, vol. xli., p. 339.

of exchanges in the solid might have been given, but only two have been chosen relating to iron to which phosphorus has been added, for which I am indebted to Mr. J. E. Stead, and the changes produced by varying the thermal treatment of an alloy of copper and tin containing 80 per cent. of copper, which is the result of the work of Mr. W. Campbell, B.Sc., in my laboratory.[1] Even the ordinary testing machine enables us to obtain an insight into molecular changes.[2] It has been shown that the stretched test-piece of steel becomes first cooler then warmer. The fall of temperature is proportional to the load up to a point below the elastic limit, and this point agrees closely with Wöhler's range for unlimited repetition of alternating stress.

Now as regards vibrations which permanently affect the structure of metals, the study of this very interesting subject is only just beginning, and I will only offer you a single case. Some years ago a young physicist, Mr. J. H. Vincent,[3] photographed, in the Royal College of Science laboratory, the waves into which the surface of mercury is thrown when it is set in vibration by a tuning-fork. The appearance of these waves will vary with the form of the walls of the vessel which reflects them. A circular receptacle presents the simplest case. They start from the vibrating point in circles and are reflected from the sides of the vessel, but agitation produced by shaking the floor causes interference of these reflected waves and a rosette-like or cellular structure is presented. But if a small quantity of pure lead or zinc be cast on glass the surface of the metal is found to be agitated by miniature whirlpools as in the case of the mercury.[4] First the reflection from a fluid bath of lead will be thrown on the screen; brilliantly coloured films of oxide soon cover the metal; yet thin as these films are they hinder the wave-like effect which was revealed on the surface of the clean mercury. Nevertheless, when the lead globule to which I have referred is cast on to glass and solidified, the microscope will show that the cell-like structure has been caught in the solid metal. In case it should be thought that these are lines of a fusible eutectic in the mass, it must be remembered that the lead was pure, only traces of foreign metals being present. This experiment will, I trust, be sufficient to show that in the near future we shall know more about the vibrations that are so destructive to steel and other structures. M. Osmond is working at the subject, so we may hope for much. It may be thought strange that vibrations in a fluid should be retained in the solid, but of late years we have had to modify very materially our conception of solids; they behave, as we have seen, much like fluids. Nothing could show this better than the beautiful results obtained by Prof. Ewing (himself a "James Forrest" lecturer), in conjunction with Mr. Rosenhain, on the growth of crystals in so-called solid metal.

There is one other great engineering work in which the efforts of the metallurgist have been very marked. I refer to the Alexander III. Bridge at Paris which crosses the Seine in a single span, and in the contruction of

[1] *Proceedings Institution of Mechanical Engineers*, 1901, p. 1211.

[2] C. A. P. Turner on "Thermo-Electric Measurement of Stress." *Transactions of the American Society of Civil Engineers*, vol. xlviii., p. 140.

[3] *Phil. Mag.*, vol. xliii., 1897, p. 411; vol. xlv., 1898, p. 191; vol. xlvi., 1898, p. 290; vol. xlviii., 1899, p. 338.

[4] This subject is being studied by Mr. Osmond, who contributed a beautiful memoir on the subject to the Association pour l'essai des Matériaux. Congres de Budapest, 1901.

which 2,200 tons of cast steel were employed. The material used in this great work, by the distinguished engineers Messrs. Résal and Alby, was treated in a peculiar way. The different sections in which the bridge was cast were raised to a temperature of about 1,000° C., and then "quenched," as it were, by rapid cooling in air to about 600°, followed by very slow cooling to the ordinary temperature. It would lead me far beyond the limits of this lecture if I were to attempt to explain the molecular changes which take place in the solid metal and are involved in such treatment; but it may be added that the metal so treated becomes stronger and more elastic and resists shock better than if it had been annealed. This bridge, which, as so many of us felt, expressed the genius of the Exhibition of 1900, presents us with a remarkable instance of the importance of changes in the solid.[1]

To turn to another metal. Both metallurgists and engineers hope much for the action of nickel on steel, and I need only, in this connection, remind you of the remarkable process for the extraction of nickel from its ores which was submitted to you in the year 1898.[2] In this process of Dr. Mond, nickel is taken up from its ores by a gas, carbonic oxide, at a temperature of 50° to 100°, and released in the metallic form by subsequently raising the temperature of the gaseous nickel compound to 180° to 200°.

I am fully conscious how much more might have been said about the relations between the metallurgist and engineer had time permitted. I should like to have spoken of the hard, quick-cutting tool of the Bethlehem Works which astonished us so much in Paris during the Exhibition of 1900. Much might have been said as to the many uses which aluminium and its alloys are put to in engineering. We can readily imagine the use to which engineers will put aluminium in aerial navigation, from which so much is expected in the immediate future. Aluminium is rendering engineers service in the following unexpected way. A remarkable feature of modern metallurgy is the very useful action of small quantities of the rarer metals on the mechanical properties of large masses of steel. By enabling us to reduce such metals as nickel, cobalt, and chromium from their oxides, aluminium is placing a supply of the rarer metals at our service. I have dealt with this subject fully and comparatively recently in a Friday evening lecture delivered at the Royal Institution "On Metals as Fuel."[3] It will only be necessary, therefore, for me to offer a few experiments which show the intense heat evolved when finely divided aluminium acts on metallic oxides and reduces them to metal, thereby playing the part hitherto allotted to such reducing agents as carbon or carbonic oxide. (Experiments were shown.)

I should have been glad, had time permitted, to deal with the improvements in the quality of copper used in electrical engineering. I will only say that if a metallurgist were now to offer the electrical engineer such copper as was supplied in the middle of the past century he would deserve to be relegated to the immortal pillory in which St. Paul placed Alexander the coppersmith who did him "much harm." I wish I could have told you

[1] "Notes sur la construction du Pont Alexandre III." By Messrs. Résal and Alby. Extrait des Annales des Ponts et Chaussées, 1898-1900. Dunod, Paris, 1900.

[2] *Minutes of Proceedings Inst. C.E.*, vol. cxxxv., p. 29.

[3] *Nature*, vol. lxiv., p. 360. *Proceedings of the Royal Institution*, vol. xvi., part iii., 1902. See also a later Paper by Mr. Bertin in the *Bulletin de la Société des Ingénieurs Civils de France*, Aug. 1902.

how much metallurgists have aided military engineers in relation to ordnance. The question of the erosion of guns has assumed pressing importance, and I may remind you of a forgotten experiment of Count Rumford,[1] who, at the beginning of the past century, thought that the *erosion* must be due to the *corrosive* action of the products of the explosion of gunpowder in a closed chamber. He, therefore, employed a *gold* vent, and the fact that it became worn as a vent of hard steel had been, pointed to the rush of gas as the source of erosion, and not to corrosion by an acid product of combustion. The mention of military engineers reminds me of some observations in the address of Mr. T. Hawksley (the father of the President), who pointed out in his address delivered in 1872, that in no way other than by the study of ordnance and armour-plate would the Institution of Civil Engineers "serve its country better, or better promote (in the interests of peace) the advancement of practical science and its application (if events should order) to the purposes of protective warfare."

In conclusion, I can only thank the Council for having permitted me to give one of the lectures by which this great Institution will always keep the memory of James Forrest in sylvan green.

[1] *Philosophical Transactions of the Royal Society* (abridged), 1796-1800, vol. xviii., p. 142.

[*To face page* 229.

Total Carbon, 0·542 per cent.
Manganese, 0·600 ..

Total Carbon, 0·371 per cent.
Manganese, 1·009 ..

Transverse Sections of Rail Steels.

STEEL RAILS.

THE LOSS OF STRENGTH IN STEEL RAILS THROUGH USE ON RAILWAYS.

In May, 1896, Roberts-Austen was selected to be a member of a Committee appointed by the Board of Trade "to enquire to what extent loss of strength in steel rails is produced by their prolonged use on railways under varying conditions, and what steps can be taken to prevent the risk of accidents arising through such loss of strength."

The appointment of the Committee was suggested by a serious accident on the Great Northern Railway in 1895 due to the fracture of a rail when a train was passing over it.

In addition to the careful examination of the particular rail which had failed at St. Neots, the Committee selected 16 rails from among a large number which at various times were tested in their presence and portions of these selected rails were apportioned among the members of the Committee for further investigation.

Roberts-Austen was entrusted with the photomicrographic examination of these rails and in the appendix furnished by him to the Report [1] he described the methods adopted in his examinations.

Consideration was first given to the examination of entire sections of rails and then to the relation between chemical composition and the results obtained by microscopic examination. The occurrence of flaws due to the presence of sulphur slag were described and discussed, and also the influence of the relative dimensions of the grains of ferrite and pearlite.

In concluding his Report, he made the following observations :—

"It is very important that all who are responsible for the manufacture or use of steel rails should realise that steel is not the homogeneous mass it is often supposed to be, but possesses a complex structure. The nature of this structure will vary greatly with the mechanical and thermal treatment to which the metal has been subjected. The durability of the rail depends in no small measure on its structure, which may, if the specimens of steel have been suitably prepared, be revealed by the microscope. The peculiar structure of the St. Neot's rail, for instance, can be exactly imitated. A careful study of the microstructure of steel must be considered in connection with the chemical composition and the mechanical tests to which the material is subjected. If this is done there are good grounds for hope that it may be possible, without materially increasing the difficulties of manufacture, to improve the specifications for the production of steel rails, both as regards chemical composition and thermal treatment."

His conclusions were illustrated by a number of carefully prepared photographs, to which the Committee invited special attention. He expressed his great indebtedness to his assistant, Mr. W. H. Merrett, who "has most patiently and ably aided me throughout this long investigation."

[1] Report of a Committee appointed by the Board of Trade to enquire into the loss of strength of steel rails through use on railways. H.M. Stationery Office, 1900.

ON THE PHOTOMICROGRAPHY OF STEEL RAILS.

A short paper read by Roberts-Austen before the Institution of Civil Engineers in 1899, *and recorded in the Minutes of the Proceedings for that year, pp.* 36–38.

A statement was offered of the principles which guide the photomicrography of steel rails, with a view particularly to eliciting information on the important question of the practicability of deducing an "ideal" or standard quality of steel rail from the behaviour of rails which had been already abundantly tested in actual use. The paper was accompanied by six photographs taken from the central portions of rails. Reference to micro-flaws, altered surfaces of rails, and to internal slag flaws were omitted, as it was thought desirable to direct the discussion of this subject mainly to the question of the relative areas of pearlite and ferrite. For this reason, the consideration of the subject was restricted to the narrowest possible limits, and the statements were not offered to express any particular views, but merely to introduce a subject which had not so far been brought to the attention of the Institution.

EXPLOSIVES AND ORDNANCE.

In 1900 Roberts-Austen was appointed a member of a Committee of the Admiralty and War Office gathered together on the initiative of Lord Goschen (then First Lord of the Admiralty) to consider certain questions in relation to Explosives and Ordnance. It was composed of distinguished men of science who were quite independent of either of the Services.

Lord Rayleigh, President.
Sir Andrew Noble.
Sir William Crookes.
Sir William Roberts-Austen.
The Right Hon. R. B. (now Lord) Haldane.
Capt. T. G. Tulloch, R.A., Secretary.

The primary object of this Committee was to introduce a powder which would give less erosion in gun tubes, and it was more especially in this connection that Roberts-Austen's services as a metallurgist were of value to the Committee. His contributions to this part of the work derived special importance from the fact that he was able to bring the resources of photomicrography to the investigations which were undertaken.

Suggestions were also made by him in regard to tests on various kinds of steel alloyed with other metals (nickel, vanadium, chromium, etc.), and a vast number of experiments were carried out at the Research Department at Woolwich, on lines which were indicated by him. He was, it is believed, the first to appreciate the advantages gained in resistance to erosion by the addition of small quantities of vanadium to nickel steel.

In connection with the work of the Committee he made a large number of experiments in recording the rise and fall of temperature during the firing of explosives in a closed vessel. The calorimeter and pyrometer were used in conjunction with great success, and valuable results were obtained.

In relation to the question of suitable detonators and "exploders" for high explosives a large number of experiments were carried out, but his death, unfortunately, prevented the completion of this work which promised to furnish valuable information.

The following paper had been published by Roberts-Austen two years earlier (1898), and it is reproduced here by way of indicating the character of the work which he undertook in relation to these important problems.

THE ACTION OF THE PROJECTILE AND OF THE EXPLOSIVES ON THE TUBES OF STEEL GUNS.

Reprinted from the "Journal of the Iron and Steel Institute," No. 2, 1898.

This important subject has already been discussed by the Iron and Steel Institute. In 1886 the results of some elaborate experiments, conducted by Sir F. Abel and Colonel Maitland [1] at the Royal Arsenal, led to the conclusion that in a breech-loading gun, scoring is produced by the rush of the products of the explosion behind and over the shot, which acts as an air-tight plug passing through the gun. The authors of the paper, to which reference has just been made, considered that as regards relative wear of different samples of steel, chemical composition was of far less importance than the mechanical treatment to which the steel had been subjected, and it appeared that the more the steel had been worked and forged, the less it suffered from the effects of the products of the explosion. The average pressure of gas measured in the powder-chamber was about 13 tons per square inch, and it was stated that the pressure would be maintained with little diminution during the passage of the shot up to the muzzle of the gun.

All who have conducted experiments with modern artillery know how deeply the rifled bores of guns become scored and eroded during use. It has been stated that the surfaces of the bores of guns also become hardened, even after five "proof" rounds have been fired. An examination of the bores of such corroded guns by the aid of microphotography should lead to interesting results, and by the kindness of Sir Benjamin Baker the author has been able to obtain a suitable subject for investigation. It consists of a section of the "A" tube of a 4·7 inch quick-firing gun, cut at a point 167 inches from the muzzle. The total thrust between the driving face of the grooves and the driving copper ring of the projectile at this portion of the bore would be about 12 tons. It may be added that, as Sir Andrew Noble has shown,[2] in such a gun as ordinarily employed there would be no less than 60 foot-tons of energy absorbed in producing rotation of the projection.

The author is also greatly indebted to Lieutenant-Colonel C. F. Hadden, R.A., Chief Inspector of the Ordnance Department at the Royal Arsenal, Woolwich, for a portion of a 3-inch steel armour-plate, which a "glancing" shot had struck, producing an indentation 0·5 inch deep, 5·1 inches long, partly by compressing the metal and causing it to flow, and partly by tearing portions of metal from the surface of the plate. This indent was produced by an ordinary 6-pounder hardened armour-piercing projectile, and the velocity at the point of impact was 1,740 feet per second, and the striking energy would, therefore, be 126·7 foot-tons.

As regards the action which might be anticipated to occur during the erosion of an "A" tube, the following facts must be remembered. The temperature produced by the explosion of cordite, which was the propellant employed in the case of the tube in question, would be very high. The heat transmitted to the surface of the tube would, however, soon be abstracted by the mass of metal in the gun. This rapid heating of the interior of the

[1] *Journ. of the Iron and Steel Inst.*, 1886, No. 2, p. 465.
[2] *Royal Society Proceedings*, vol. l., 1892, p. 409.

Fig. 1.—"A"-tube eroded by gas.

Fig. 2.—Section of a "land" and "groove." × 3·3 diam.
(Dotted line shows original rifling of the bore.)

tube, followed by more or less rapid chilling by this transmission of the heat, might, therefore, be expected to occur. Hence there are possibilities of more or less elaborate changes due to the thermal disturbance caused by merely firing the gun. The mechanical effect of the projectile passing along the tube has also to be considered, and the results should prove to be of interest, as the effect of work in producing molecular change in steel has long been a subject of study by Osmond, Barus, Carus Wilson, and others. The explosion produced by cordite would produce in this gun so high a pressure as 15 tons on the square inch. The problem, therefore, becomes a complicated one, which micrographic examination should render it possible to readily elucidate. First as regards the composition of the steel. The tube was a perfectly normal gun-steel, containing about 0·3 per cent. of carbon and 0·6 per cent. of manganese. The respective amounts of sulphur and of phosphorus did not exceed 0·05 per cent., and the amount of silicon was not more than 0·15 per cent. As regards treatment, the tube had been oil-quenched from a temperature of about 800° C., and subsequently annealed at about 500° C. Examination with any degree of magnification exceeding 100 diameters, of a new tube in which no charge had been fired, should reveal more or less confused pearlite, produced by the annealing, traversed by bands or a network of ferrite. The transition forms of the carbide, troostite, or sorbite, might be present, but there should be no martensite. This proves to be the case in all microsections cut from the mass of the tube. If, however, a microsection be taken from either the extreme edge of a "land," or from the driving edge of a groove, a very different structure is revealed. Such examination demands special preparation of the microsection, as only the extreme edge of the "land" is changed, sometimes only to a depth of $\frac{2}{1000}$ of an inch. It is necessary, therefore, to imbed the metal in a piece of steel of similar carburisation and hardness, and to polish the whole. This protects the edge of the metal, which is of interest, from being rounded during polishing, and as the whole of the microsection remains flat, it is possible to focus in the same plane. The result of a thorough examination proves that the action of the explosive has, so far as the mass of the tube is concerned, been purely mechanical. The particles of steel have been simply eroded, and there is no evidence of fusion or of the formation of martensite. But at the extreme edge of the "land," or on the driving edge of the groove, both of which have been in direct contact with the driving bands of the projectile, and have been pressed by them, there is an altered layer, often only $\frac{2}{100}$ of an inch deep, which has been profoundly altered. The most noteworthy feature is that the ferrite bands seldom pass into this altered layer; they either stop short or fade away as they approach the altered edge. As regards the nature of this band which forms the altered edge, it is difficult to speak with certainty, but in some cases it seems to be a confused mixture of carbides. If the steel had been superficially changed into ordinary hardened steel, the altered layer would, of course, consist of martensite, but the presence of frankly developed martensite could not be detected. This suggests the question whether sufficient time elapsed while the metal was undergoing change for the complete diffusion of the carbon in the layer. So far as is at present known, the formation of martensite would demand this complete diffusion of the carbon. It is even possible that the layer may be a deposited one, composed of the detritus of the eroded matter. Against this view there

is the fact that in some cases the ferrite bands fade away as the altered layer is approached. In other cases fine lines of ferrite pass into the altered layer. My friend M. Osmond (of whose counsel I have gladly availed myself) considers that, in a matter of so much importance, it would be unwise to express a definite opinion at present.

I have elsewhere [1] shown that when a projectile strikes an armour-plate it may, under certain conditions, produce in the solid steel a "splash" which resembles that produced by a sphere falling into water. I have also [2] shown that the penetration of carbon into iron obeys the ordinary law of diffusion of salts into water.

It is noteworthy that the surface of the "lands" over which the projectile has passed are traversed by cracks at right angles to the length of the "lands."

With reference to the armour-plate struck by a glancing shot, to which reference has been made, I do not find that the microstructure of the armour-plate has been altered by the impact.

[The paper was illustrated by a series of microphotographs, carefully prepared by Mr. W. H. Merrett. Four of these are reproduced, Plates XIV. and XV.]

Plate XIV., Fig. 1, shows the section of the "A" tube eroded by gas. Fig. 2 is a section of a "land" and "groove," the dotted line showing the original rifling of the bore of the gun. It will be evident, therefore, how much material has been removed by erosion. The magnification is in this case about 3·3 diameters. Plate XV., Fig. 1, is a plan of a "land" and "groove," showing the eroded surfaces. The lighter portion is the raised "land," and it will be observed that there are transverse fissures.

Fig. 2 shows a section, magnified 117 diameters, of the driving edge of the groove. It will be seen that the altered layer resembles a geological deposit, and probably consists of eroded matter transferred from another part of the bore and welded in position. The white network of ferrite does not pass into this deposited layer.

There is also a portion of metal near the top of the driving edge in Fig. 4 which is nearly free from the ferrite network, and clearly shows an altered structure which is quite distinct from the deposited layer. This upper portion of the driving edge sustains the maximum pressure of the driving band of the projectile, and is altered by the friction it produces.

[1] British Association, Discourse. Toronto, 1897. *The Times*, Aug. 23, 1897.
[2] *Journ. of the Iron and Steel Inst.*, 1896, No. I., p. 139, and pp. 247-8 of this volume.

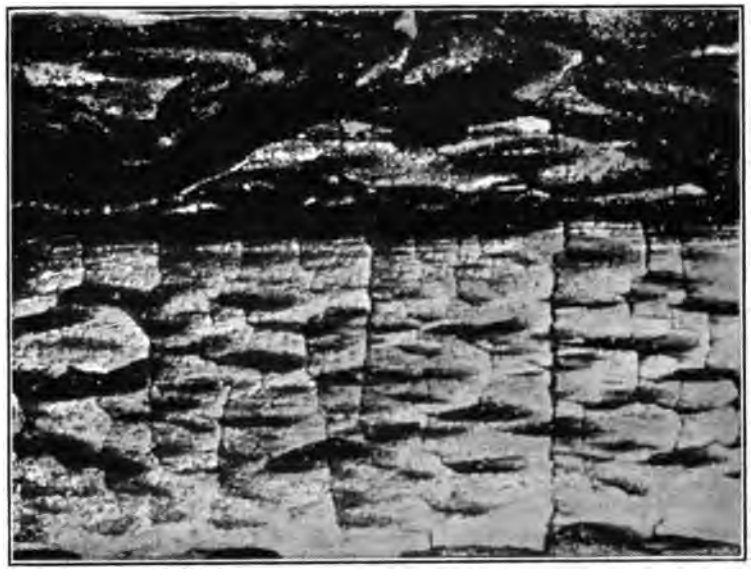


Fig. 1.—Plan of a "land" and "groove" showing the eroded surfaces.

Fig 2.—Section of the driving edge of the "groove." × 117 diam.

SOME MISCELLANEOUS PAPERS IN RELATION TO THE METALLURGY OF IRON AND STEEL.

EXPERIMENTS MADE TO ASCERTAIN WHETHER OCCLUDED GASES PLAY ANY PART IN THE HARDENING AND TEMPERING OF STEEL.[1]

(*The Report of a Committee of the Institution of Mechanical Engineers on the Hardening and Tempering of Steel*, 1881.)

[In this paper, the belief, which had some currency at the time (1881), that occluded gases play a part in the hardening and tempering of steel, was finally disposed of, and the sound views held by Réaumur in the eighteenth century were established in their true place with regard to the constitution of steel.]

The first report of this Committee, after considering the various theories as to the causes of the hardening and tempering of steel, concludes as follows:—[2] "May it not be that the sudden contraction in hardening steel has the effect of expelling occluded gases: that the subsequent tempering, by raising the temperature, has the effect of permitting a fresh absorption; and that the iridescent colours which accompany the tempering are due to the change of surface caused by the infiltration of gases? Another view is that the mere heating of steel to the proper temperature for hardening is sufficient to expel a portion of these gases, which are kept out by sudden cooling, and are slowly re-absorbed in tempering. . . . May not steel, therefore, possess properties analogous to platinum and palladium, with respect to some of the gases constituting the air? May it not absorb these more fully as the temperature of tempering rises, and so gradually become restored to its original softness?"

There is much in the evidence afforded by recent researches to lend probability to this view; and few questions connected with the metallurgy of iron and steel are attracting more attention than the relations between the metal and the gases with which it comes in contact during the processes of manufacture. The question of the intervention of gas in the carburisation of iron has long been recognised as one of great interest. Bergman, writing in 1781,[3] was the first to show that the difference between malleable iron, steel, and cast iron depends on the amount of carbon the metal contains, and it may be well to remember that he was led to the opinion that "fixed air" could give up its carbon to iron; so that the importance of the relation between iron and gases was indicated in the researches which were the first to give us accurate knowledge as to the true nature of steel.[4]

[1] *Proceedings of the Institution of Mechanical Engineers*, Oct. 1881, pp. 706-711.

[2] *Proceedings of the Institution of Mechanical Engineers*, 1881, p. 692.

[3] "De Analysi Ferri." *Opuscula Physica et Chemica*, vol. iii., 1783.

[4] Kirwan, R., "Essay on Phlogiston and the Constitution of Acids," 1787, p. 140. "If a bar of soft iron be put into a crucible, well covered and luted, without any addition, and kept at a welding heat for eleven days, it will be converted into steel. . . . Here it is plain that charcoal could not penetrate through the crucible, but fixed air easily can. . . . The plumbago then clearly owes its origin to this air, as Mr. Bergman explains it."

Margueritte [1] in 1865 repeated an experiment made at the close of the last century by Clouet, employing the diamond as a source of carbon. Margueritte's experiments were conducted under conditions that rendered the results unequivocal; and he showed that, although the carburisation of iron can be effected by simple contact with solid carbon, it is nevertheless true that, in the ordinary process of cementation, carbonic oxide plays an important part, which had previously been overlooked.

Graham's paper on the occlusion of gases by metals,[2] which appeared a year later, showed that carbonic oxide could penetrate to the centre of a mass of heated iron, and thus gave special point to Margueritte's work. The latter experimentalist had, as Graham himself observes, made the action of a high temperature very clear—the carbonic oxide being introduced into the iron at a comparatively low temperature, while a high degree of heat is subsequently necessary, to enable the metal to appropriate the carbon and become steel. Graham's experiments showed that wrought iron occludes six or eight times its volume of carbonic oxide; and he urges that the way in which the qualities of iron are affected by the presence of a substance in no way metallic in its character—locked up in so strange a way, but capable at any time of reappearing, under the influence of heat, with the elastic tension of a gas—is a subject which metallurgists may find worthy of investigation. This suggestion has already led to important results. I hope in a subsequent communication to examine the evidence on which the present views, as to the gases occluded by iron and steel, really rest. At present I would limit myself to the question raised by the Committee, to which reference has already been made.

It appeared necessary in the first place to ascertain whether steel will "harden" when rapidly cooled in vacuo—that is to say, under conditions in which access of gas is impossible. The first step is to deprive the steel, which forms the subject of an experiment, of the gases that it has already occluded during the process of manufacture; for experience has shown that it is not safe to deal with steel, in experiments of this kind, until the gases—whether pre-existing or self-produced by the reactions between the impurities it may contain—are first extracted from the metal. This, however, is by no means an easy matter. Six strips of steel were selected, each about 127 mm. long, 3 mm. wide, 1·2 mm. thick (5 ins. × 0·118 in. × 0·047 in.): the total weight of the six being 22·5 grammes (347 grains). These were enclosed in a porcelain tube, connected in the usual way with a Sprengel air pump. The metal was strongly heated in the vacuo for twenty-six hours, at the end of which time the evolution of gas had practically ceased, and 27 c.c. of gas (1·6 cub. in.), or 9·31 times the volume of the metal, had been extracted. In this particular case the gas was not analysed. The proportion of the constituent gases varies widely during the period of extraction, but in other similar cases I have found the mean composition to be about $\frac{1}{2}$ hydrogen, $\frac{1}{3}$ carbonic oxide, and $\frac{1}{6}$ carbonic anhydride.

If a strip of the steel thus deprived of gas be heated, and cooled in vacuo, it is easy to ascertain whether hardening has been effected, and, if it has,

[1] "Recherches sur l'aciération," *Ann. de Chim et de Phys.*, t. vi. (4), 1865, p. 55.

[2] "On the absorption and dialytic separation of gases by colloid septa," *Phil. Trans.*, vol. clvi., p. 436, 1866.

whether the change in the steel is accompanied by a further evolution of occluded gas, which would, of course, destroy the perfection of the vacuum.

The experiment may be conducted in several ways. In one case a strip of the steel above-mentioned was placed in a porcelain tube rendered vacuous by means of the Sprengel pump, by the aid of which the vacuum could be readily maintained. At one end of the porcelain tube a bent glass tube was fixed, which contained mercury previously boiled to free it from air. The mercury was again boiled in vacuo, in order to drive over any air it might retain, and allowed to cool. The portion of the tube containing the steel was then heated to bright redness, and, without detaching the tube from the pump, the heated metal was tilted rapidly into the reservoir of mercury, about an inch of the metal being actually submerged in the fluid. This portion afterwards proved to be of a degree of hardness that would readily scratch glass.

The end of the steel that had not touched the mercury, of course, remained soft. It will be obvious, therefore, that steel will harden under conditions in which there are no gases for it to absorb; and, as the mercury column in the pump remained undepressed, no occluded gases were evolved during the hardening. With regard to the suggestion of the Committee that the characteristic colours produced in tempering steel may be due to the absorption (as distinguished from oxidation) of gas, I would point out that hardened steel may be tempered by heating and slow cooling in vacuo, and, in the absence of air, the metal does not sensibly change colour.

On heating steel in vacuo in a porcelain tube, care must be taken to prevent contact with the siliceous walls of the tube; otherwise the carbon of the steel, as Troost and Hautefeuille have shown,[1] will reduce the silicate, and the consequent evolution of carbonic oxide will render it impossible to maintain a perfect vacuum. In the experiment I have described, care was taken to keep the steel from the sides of the tube by platinum studs. Before the steel was tilted into the mercury the evolution of gas had entirely ceased, and the mercury stream of the pump fell with the sharp click that indicates a good vacuum.

The experiment may be varied by heating a spiral of steel wire to redness in vacuo by means of an electric current, as Edison did in his well-known experiments on the effect of high temperatures on metallic wires. When the evolution of bubbles of gas has ceased, the apparatus is turned, so as to bring the incandescent wire in contact with mercury. The portions of the wire that touch the mercury become glass-hard, and the ends that cool slowly remain soft.

It is hardly necessary to point out that Réaumur, the great authority of the eighteenth century on the conversion of malleable iron into steel, when he published his singularly advanced work on the subject in 1722, was not aware of the importance of the part played by carbon; for he says,[2] "We now know that steel only differs from iron by being more penetrated with sulphurs and salts." I was not aware, however, until after I had made the above experiments, that Réaumur's views, as to the characteristic property which steel possesses of hardening when heated and rapidly cooled, were of so much interest; and indeed the experiments on which his conclusions

[1] *Comptes Rendus*, 1873, pp. 482 and 562.
[2] "L'art de convertir le fer forgé en acier," Paris, 1722, p. 320.

were based seem to have been generally overlooked or forgotten. In the work to which I have already alluded, he says,[1] "As a second explanation I would suggest one according to which the hardening depends on a substance being driven from between the particles by heat, its return being stopped by the water. I confess this took my fancy very much at first. It appears natural to suspect the existence of enclosed air, which is pressed between the particles of the untempered steel. Where is there not air? May not this air, by tending to separate the particles of the steel, hinder them from holding well together? But the fire, by expanding the steel and opening the pores, drives away this air, to which all entry is stopped when one cools the metal suddenly, instead of letting the same air return little by little into the steel as it gradually loses heat." He satisfied himself that this explanation was not correct, by allowing a piece of red-hot steel to cool slowly in the *best Torricellian vacuum he could secure.* A piece of hot steel was attached to a plug fixed by a layer of wax or resin inside the top of a long upright tube nearly filled with mercury, so as to leave a small space of air surrounding the steel. The mercury was then allowed to fall, and thus produced a highly rarefied atmosphere, in which the steel was slowly cooled. On removal it proved to be perfectly soft.

The question then of the true cause of the hardening of steel remains much where Réaumur left it when he stated[2] that, "since the hardening of steel is neither due to the introduction of a new substance nor to the expulsion of air, it only remains for us to seek its cause in the changes occurring in its structure," or, it may be added, in the mode of existence of the carbon in the metal.

[1] *Loc. cit.*, p. 317. [2] *Loc. cit.*, p. 319.

STEEL FOR THE MANUFACTURE OF DIES.

(Part of the Appendix to the "Eleventh Annual Report of the Deputy Master of the Mint," 1881.)

I have referred in former Reports[1] to the question of steel for the manufacture of dies, and attention has frequently been drawn to the difficulty experienced in obtaining metal of suitable quality. Our knowledge of the relation between the chemical composition and the mechanical properties of steel may also be said to have been created since 1849, when the late Prof. Brande stated, in evidence before the Royal Commission on the Mint, that he had analysed numerous varieties of steel, but ascribed its peculiarities more to mechanical texture than to chemical composition.[2] Not long since, the appearance of the fracture of a sample of metal was considered to afford trustworthy and sufficient evidence as to its nature and properties; but such rough methods have now given place to the rigorous physical, chemical, and mechanical investigations to which metals must be submitted as a matter of ordinary routine.

[The chemical compositions of various samples of die-steel were then discussed at some length and the report then continues—]

It would appear that the extensive experience of the Mint in the use of steel for dies might be expected to afford valuable information as to the conditions to be satisfied by the metal in order that it may be specially adapted for such a purpose; but the many slight variations of condition, the difference in the denomination of coin struck (and, therefore, in the pressure applied), and in the character of coining press used, render it impossible to draw other than general conclusions from the ordinary work of the Department.

Turning to the general investigations which have been made into the resistance of metals, it is to be observed that very little information is available which can be regarded as strictly bearing on the question of dies. The direct tests for resistance to impact—as, for example, those applied to armour-plates—cannot be considered to afford a guide in the selection of steel for such a purpose; and even if they could be accepted in relation to impacts like those of a coining press, the operation of hardening is of so delicate a nature, and its influence on the physical properties of the metal is so little understood that any conclusions would probably require considerable modification in practice.

Nevertheless, it may be well to note the basis on which these tests are made. Kirkaldy[3] concludes, as the result of experiments, that the contraction per cent. where rupture occurs in the usual form of test-piece affords very trustworthy information as to the value of steel. Prof. Åkerman,[4] of Stockholm, takes the fraction formed by dividing the limit of elasticity (usually expressed in tons per square inch) by the breaking strain, expressed

[1] Report on European Mints; Parliamentary Paper 466, 1870, p. 27; Eighth Annual Report, 1877, p. 40; Ninth Annual Report, 1878, p. 39.

[2] Minutes of Evidence, Royal Mint Commission, 1849, p. 181.

[3] "Experiments on Wrought Iron and Steel." By David Kirkaldy, p. 91.

[4] *Journ. of the Iron and Steel Inst.*, 1879, No. 2, p. 504.

in the same terms, as a coefficient, and Deshayes [1] prefers to adopt the difference between these two numbers as a measure of the power of a given sample of steel to resist impact.

It is, however, important to notice that the coefficient here referred to indicates the extreme force which the metal will support, and thus cannot be applied to the case of a die, which is subjected to a prolonged series of impacts, the force of which is considerably under that at which crushing would occur. A somewhat analogous case—that of steel in a constant state of vibration, as the springs of railway carriages—has been investigated by Wöhler,[2] and he concludes that the difference in the tension of the metal at the extreme limits of each vibration may be taken as a measure of its resistance. He further states that the amount of the tension may be increased in proportion as this difference becomes less.

It is to be observed that Åkerman's criterion for resistance to impact is also a criterion for ductility, for the smaller the ratio $\frac{L}{R}$ (L being the limit of elasticity and R the breaking load) becomes, the greater is the force beyond the limit of elasticity that the substance can resist without fracture, and the tougher accordingly it is. But in hardened steel the limit of elasticity is increased so as to approximate to the breaking load, and the ductility together with the resistance to shock will thus diminish, as is indicated by the increase in the value of the fraction $\frac{L}{R}$. This fraction appears to afford one datum for determining the properties that characterise a good die-steel, but Åkerman himself points out that it has not yet been sufficiently studied even by engineers, and it is impossible for me to say how far it bears on the question under consideration.

In addition to resisting shock, a die-steel is required to satisfy yet another important condition. It must retain the precise form given to it, so that the engraved device is not distorted by the impact; or, in other words, the steel must have a high limit of elasticity. As is well known, such a condition is best satisfied by hardening the metal, but, when this is done, the rules above given for determining resistance to impact in all probability become less applicable.

With a view to ascertain the mechanical properties which characterise a good die-steel, samples have been submitted to Prof. Kennedy, M.Inst.C.E., of the University College, London, for trial in the special machines employed for testing metals. [The results were given in accompanying tables.]

[This question of steel suitable for the manufacture of dies continued to receive attention from Roberts-Austen from time to time. Reference has already been made (p. 23) to the fact that this was one of the first uses to which he applied the methods of photomicrography. In the Mint Report for 1896 the question was reviewed from this point of view, and striking photomicrographs were published in illustration of the evidence which had been obtained in this way (see Plate XVI.).]

[1] "Classement et Emploi des Aciers," p. 96.

[2] Uber die Festigkeitsversuche mit Eisen und Stahl. Berlin, 1870. See, however, letters by Prof. Kennedy in *Engineering*, 1880, pp. 206, 246, 286, 328.

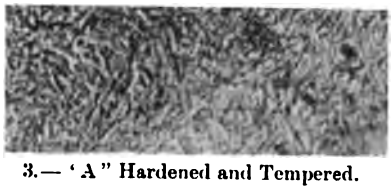
[*To face page* 240.

STEEL USED FOR DIES.

Good Steel.

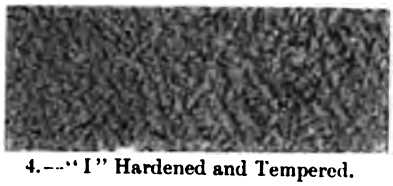
1.—"A" Soft.

Good Steel.



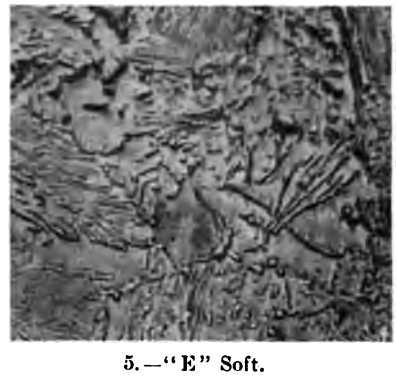
3.—'A" Hardened and Tempered.

Bad Steel.



4.—"I" Hardened and Tempered.

Good Steel.



5.—"E" Soft.

Bad Steel.

2.—"I" Soft.

[The first Photo-Micrographs published by Roberts-Austen (1896).]

THE ELECTRO-DEPOSITION OF IRON.

Reprinted from the "Journal of the Iron and Steel Institute," No. 1, 1887.

The great interest which would attend the investigation of the properties of pure iron has long been recognised, and although but few results have as yet been obtained, elaborate preparations for such an inquiry have from time to time been made. A committee appointed by the British Association described in 1869 [1] a method which yielded iron of a high degree of purity, the work being entrusted to the late Prof. Matthiessen, who ignited pure ferrous sulphate mixed with sodium sulphate, reduced the oxide of iron so obtained by pure hydrogen, and melted the spongy iron in a lime crucible before the oxyhydrogen blowpipe. The committee reported that: "With regard to the physical properties of pure iron, owing to want of time, nothing has as yet been accurately determined. It appears, however, that many of the physical properties of the pure metal differ considerably from those of the commercial." The work appears to have been interrupted by Matthiessen's lamented death, which occurred in the following year. It may be that metallurgists have been satisfied that Bessemer metal, proved by analysis to contain no carbon or silicon, and only 0·031 per cent. sulphur, 0·014 per cent. phosphorus, and 0·05 per cent. manganese, is sufficiently pure to afford a basis for investigation, without resorting to elaborate chemical methods of preparation, for but little has hitherto been done with a view to prepare on a large scale a material in which the above-mentioned impurities are entirely absent.

The volume of the Reports of the British Association, to which reference has just been made, also embodies a paper by M. H. Jacobi, of St. Petersburg, whose name is so well known in connection with electro-metallurgy. M. H. Jacobi and M. Eugene Klein took out a patent in this country in 1869—No. 2,456—which was, however, allowed to lapse at the end of that year. Jacobi worked for some days in the Mint laboratory, and communicated to me the details of the methods of manipulation, and in 1870 I visited St. Petersburg and had the advantage of seeing the iron deposited on a large scale with a view to the preparation of plates to be used for printing the paper money of Russia.

The deposition of iron is attended with many difficulties. In this country, so far as I know, iron has only been deposited electrolytically on a very small scale, and the metal deposited has been considered rather as a metallurgical curiosity than as possessing any practical value.

It may be well to describe briefly the method of procedure. The bath used is a solution of ferrous sulphate and magnesium sulphate in equivalent proportions, of specific gravity 1·155. The solution must be so far neutralised by the addition of magnesium carbonate that blue litmus paper barely shows any acid reaction. A wrought-iron anode, of about the same size as the object which is to receive the deposit, must be employed, and the best interval between the poles proved to be about 4 cm.

The secret of success appears to lie in the use of very feeble currents. Mr. W. H. Preece, F.R.S., Electrician to the Post Office, has kindly afforded

[1] *Report* for 1869, p. 82.

me facilities for the determination of the strength of the currents employed. It may be sufficient to state that the current best suited for the deposition of an iron medallion, the surface of which measured 560 sq. cm., proved to have a strength of only 0·089 ampere, and such a current was yielded by two Smee's cells, each having a silver plate of 50 sq. cm. area, coupled up in series.

The only objection to the process is the length of time required for its completion. It was not found possible to deposit such a medallion, of sufficient thickness for use in the reducing machine, in less than three weeks. The adherence of the deposited iron to the surface of the copper gives rise to considerable difficulty in detaching it; and, in order to reduce this adherence, it was found best to throw down on the copper mould a thin film of nickel, and, after exposing this for a short time to the air in order to slightly tarnish its surface, to cover it with a second film of nickel on which the iron was subsequently deposited. Even when this precaution was taken, several moulds were spoilt by partial adherence of the iron and copper to the nickel. I am now conducting some experiments on the deposition of iron on copper moulds covered with a thin layer of silver iodide, that substance being well known as an excellent conductor.

The metal has a high degree of purity. Mr. A. Wingham, a skilful analyst in my laboratory at the Royal School of Mines, finds that a specimen submitted to certain physical tests, to which reference will be made presently, contained only the slightest trace of magnesium, and 0·005 per cent. of sulphur. Its density is 7·675, which becomes 7·811 when the metal is annealed. By annealing carefully measured strips of metal, they were found to contract about 1 per cent. of their length. I found in 1869 that the metal, as deposited, occludes from seventeen to twenty times its volume of hydrogen. Cailletet showed [1] that iron deposited under certain conditions occludes 248 times its volume of hydrogen, the presence of which gas renders the metal very hard, and augments considerably its coercive force when magnetised. Notwithstanding the purity of the metal, its magnetic capacity does not appear to be high. Tested by the magnetic balance designed by Prof. Hughes, it would appear to possess less than two-thirds the magnetic capacity of a strip of Russian sheet of the same dimensions.

The magnetic capacity of the strip of electro-iron rises considerably when the metal is annealed, which tends to show that the defective magnetic quality is due to the state of aggregation of the metal and not to impurity, as well as to the partial expulsion of the occluded gas. With a view, however, to set this important question of magnetic capacity at rest, I have deposited on a carefully turned rod of copper 1·01 feet in length and 0·511 inch in diameter, electro-iron of a maximum thickness of 0·035 inch. Dr. John Hopkinson having expressed a wish to conduct some experiments in this direction, the rod (now exhibited) will be placed in his hands.

From the point of view of its molecular structure the electro-deposited iron promises to afford interesting experimental results. Strips of the iron, about 5·4 inches in length, 0·033 inch in thickness, and 0·75 inch in breadth, were tested for tensile strength. It was found that the deposited metal crushed in the jaws of the machine, and it was, therefore, necessary to anneal the

[1] *Comptes Rendus*, t. lxxx., 1874.

ends of the test-piece before submitting it to stress. A piece of deposited iron so treated broke in the centre of the strip with a load of 2·7 tons per square inch. A similar strip, annealed at the temperature of molten zinc—about 412° C.—was found to possess a tensile strength of 13½ tons per square inch; and another piece, annealed at a temperature between the melting point of silver—940° C.—and that of the melting point of aluminium—or about 800° C.—had a tenacity of 15½ tons per square inch, two separate experiments agreeing very closely. The elongation was in each case very small, and delicate instruments would be required to determine its amount with accuracy. It will be possible in further experiments to examine by photographic methods described by Mr. Sorby the change in structure from a pure, brittle, and non-coherent metal to one having a considerable tenacity.

The use of the electro-deposited iron for printing purposes has already been mentioned. One other application remains to be described.

Many years ago I suggested that electro-deposits of iron should be employed with a view to test the capabilities of a machine devised for reducing designs modelled in low relief, and the reproductions in metal and ivory were so faithful that the superiority of such iron deposits to the metal casts or copper electrotypes ordinarily employed was at once demonstrated.

The preparation of the dies for the coins to be struck on the occasion of the jubilee of Her Majesty the Queen presented a favourable opportunity for the more extended application of similar deposits of iron. The designs, modelled in plaster, were reproduced in intaglio by the electrolytic deposition of copper, and on the copper moulds so prepared iron was deposited. The iron proved to be hard, and of excellent quality, and up to the date of this paper obverse dies of all denominations of gold and silver coin, as well as the obverse of a medal, have been produced by a reducing machine from such deposits, the maximum thickness of which is nearly $\frac{1}{10}$ of an inch.

ON THE CARBURISATION OF IRON BY THE DIAMOND.

Reprinted from the "Journal of the Iron and Steel Institute," No. 1, 1890.

That the presence of carbon determines the physical properties of iron is universally recognised. It is, however, a singular fact that the mass of recent work, both theoretical and practical, which has clearly shown the importance of the presence in iron of elements other than carbon, and has enabled the nature of their action to be defined, has in no way lowered the position which carbon holds as the element which confers upon iron the wide range of properties characteristic of steel. It is also strange that, notwithstanding the wealth of literature which relates to the history of the extraction of iron from its ores, and its conversion into steel, but little has been written with reference to the historical experiments by which the true nature of the steel, as distinguished from iron, was established.

I do not propose to do more than briefly allude to the writings of what may be called the critical period of the history of theoretical views concerning the constitution of steel. The period was a brief one, as it only extended over the seven years that intervened between 1774 and 1781. In 1774 Rinman showed that a drop of nitric acid simply whitens wrought iron, but leaves a black mark on steel; while in 1781 Bergman [1] clearly stated that steel mainly differs from iron by containing $\frac{3}{10}$ per cent. of carbon, while iron does not. The great professor at the University of Upsala was, as I have elsewhere shown,[2] not only one of the earliest workers in the field of thermo-chemistry, but a believer in the polymorphic nature of iron. The history of the metallurgy of iron at the end of the eighteenth century is, in fact, an epitome of the history of chemistry at that period. Bergman tenaciously held to the phlogistic theory in relation to steel; it was inevitable that he should. The true nature of oxidation had been explained by the school of Lavoisier; no wonder that the defenders of the phlogistic theory should seek to support their case by appealing to the subtle and obscure changes produced in iron by apparently slight causes. Bergman's view was, however, combated by Vandermonde, Berthollet, and Monge,[3] who showed, in a report communicated to the Académie des Sciences in 1786, that the difference between the main varieties of iron is determined by variation in the amount of carbon, and, further, that steel must contain a certain quantity of carbon in order that it might possess definite qualities.

Bearing in mind the nature of Black's work, it was only natural that he, writing in 1796,[4] should have attributed the hardening of steel to the "extraction of latent heat"; "the abatement of the hardness by temper being due," he says, "to the restoration of a part of that heat." Osmond in the last few years has shown that such evolution and absorption of heat is the thermal evidence of molecular change in iron, which lends additional interest to the observations of Black; but, to return to the period at which

[1] *De Analysi Terri Opuscula Physica et Chemica*, vol. iii., 1783.

[2] "On the Hardening and Tempering of Steel," *Nature*, Nov. 7-14, 1889, and pp. 154-175 of this volume.

[3] *Histoire de l'Academie Royal des Sciences*, 1786 (printed 1788), p. 132.

[4] *Lectures on the Elements of Chemistry*, vol. ii., 1803, p. 505.

he wrote, it is quite evident that the great English chemist did not see that the work of Bergman had entirely changed the situation, and even we are apt to forget how necessary it was at the time to establish the fact that carbon is really the element which gives to steel its characteristic properties.

With this object in view, Clouet in 1798 melted a little crucible of iron weighing 57·8 grammes containing a diamond weighing 0·907 gramme, and obtained a fused mass of steel. Guyton de Morveau [1] reported upon this classical experiment, which was repeated by many observers in this country, none of whose results were free from doubt which arose from the fact that furnace gases could always obtain access to the iron, and might, as well as the diamond, have yielded carbon to the metal. The question, however, of the direct carburisation of iron by the diamond has never been really questioned since 1815, when a working cutler, Mr. Pepys,[2] employed the electric current to heat iron wire and diamond dust together, and obtained steel. Nevertheless, as his experiment was performed in air, the possibility of the formation of a gas containing carbon was not entirely eliminated. The question whether the presence of gas as well as of solid carbon is really necessary to effect carburisation seems to have had singular attraction for experimenters. Margueritte,[3] for instance, in 1865 repeated Clouet's experiment, and showed that, although carburisation can be effected by simple contact of carbon and iron in a gaseous atmosphere, it is nevertheless true that in the ordinary process of cementation the gas carbonic oxide plays an important part, which had until then been overlooked.

Graham [4] insisted upon this fact in his classical paper on the "Occlusion of Gases by Metals," in which he described the discovery of the occlusion of carbonic oxide by iron.

The journal of this Institute for 1885 [5] contained a reference to the interesting experiments of Hempel,[6] who found that the diamond form of carbon unites more readily with iron than either the graphitic or the amorphous form. He employed pure colourless diamonds, which had previously been heated in an atmosphere of nitrogen, and one result of this experiment was to show that solid carbon does not carburise iron at a temperature below a red heat, provided the carbon and iron be heated in an atmosphere of nitrogen perfectly free from oxygen.

It has, however, been asserted that nitrogen is a powerful agent in the conversion of iron into steel, and for reasons which cannot be dealt with here, I am inclined to think that it is so. But the question as to carburisation was reduced by Hempel's experiments to very narrow limits, and I determined to repeat Clouet's experiments, using a vacuum instead of an atmosphere of gas. The form of the apparatus used rendered it possible not only to use the electric current for heating pure electrolytic iron in vacuo in the presence of diamond, but to heat the iron itself in vacuo before contact with the diamond was effected, and thus to deprive the iron of its occluded gas.

[1] *Ann. de Chim.*, vol. xxxi., 1799, p. 328.
[2] *Phil. Trans. Roy. Soc.*, 1866, pp. 399-439.
[3] *Ann. Chim. et Phys.*, t. vi. (4), 1865.
[4] *Phil. Trans. Roy. Soc.*, 1866, pp. 399-439.
[5] *Journ. of the Iron and Steel Inst.*, 1885, p. 298.
[6] *Ber. der deutsch-chem. Gesellschaft.*, vol. xviii., p. 998.

I am satisfied that combination of iron and diamond does not take place until a full red heat is reached, which agrees with Hempel's statement as regards the experiments conducted in an atmosphere of nitrogen. It would, however, be well to repeat my experiment, making accurate thermal measurements by the aid of Le Chatelier's pyrometer.

It may be pointed out that these simple experiments derive their theoretical interest mainly from the assertion that no two elements can react on each other unless a third element or substance be present. It would appear, however, that a mere "trace" of such additional element is sufficient to ensure combination; for in the experiments I have described, carbon and iron, in their purest obtainable forms, were used, and the only additional matter which could have been present was the trace of occluded gas which the iron may have retained.

It is safe, therefore, to conclude that carbon can combine with iron in vacuo at a full red heat. I have thought it well to bring this fact forward at the present time, for we have seen, from M. Osmond's paper, that, after more than a century of research, carbon still retains its place as the chief element which modifies the properties of iron. The interest in its action is now more intimately connected with the molecular changes in the iron which it is capable of producing than with its own direct association with the metal.

ON THE RATE OF DIFFUSION OF CARBON IN IRON.

Reprinted from the "Journal of the Iron and Steel Institute," No. 1, 1896.

This communication is a somewhat slender one, and is mainly intended to direct attention to a subject which has been too long neglected, although experiments directly connected with it have from time to time been submitted to this Institute. The conversion of iron into steel by the passage of *solid* carbon to the centre of a *solid* mass of iron is one of the oldest facts recorded in scientific literature. The name "cementation" had been given to it from its analogy to another process of great antiquity, the removal of silver from *solid* gold plates by the action of a cement, a process which was accurately described by Geber in the eighth century, and was used by the Chinese, centuries before our era. Scientific interest in the process may be said to date from the time of Bergman, who in 1781 pointed to the carburisation of iron as the cause of its conversion into steel. As regards the cementation of iron by carbon, which constitutes the old method of steel making, Le Play in 1846 considered it to be "an unexplained and mysterious process," and he attributed the transmission of carbon to the centre of the iron solely to the action of carbonic oxide. Gay-Lussac confessed that a study of the process "shook his faith in the belief generally attributed to the ancient chemists that *corpora non agunt nisi soluta*, . . . for it is certain," he adds, "that all bodies, solid, liquid, or aëriform, act upon each other; but of the three states of bodies the solid state is the least favourable to the exercise of chemical affinity." This statement of Gay-Lussac's clearly points to the existence of fluid molecules in a mass, which is, as a whole, solid, and it also leads to the belief that solids may diffuse in each other. I have already traced the history of the diffusion of solids in the Bakerian lecture delivered in February last [1] before the Royal Society. In it I refer to some experiments of my own which show that *solid* gold or *solid* platinum will diffuse into solid lead even at the ordinary temperature, while the rate of diffusion becomes singularly rapid if the temperature of the lead be raised to 150°.

The process of cementation has been exhaustively studied by Mannesmann,[2] but as regards, however, the diffusion of carbon, in 1881 M. A. Colson communicated a paper to the *Academie des Sciences*, in which he attempted to measure the diffusion rate of carbon in iron, and showed that when iron is heated in carbon there is a mutual interpenetration of carbon and iron at so low a temperature as 250°. This work, it should be mentioned, was led up to by that of Marsden, Violle, and other experimenters, some of whom demonstrated that solid carbon will permeate strongly heated porcelain.

I may add that any lingering doubt as to whether gas need necessarily intervene in the cementation of iron was removed in 1889 by an experiment of my own,[3] by which I endeavoured to complete the series of experiments on the carburisation of iron by the diamond which, beginning with Clouet's work in 1798, was continued by a host of experimenters down to Margueritte,

[1] *Trans. Roy. Soc.*, Bakerian Lecture, 1896, also pp. 282-297 of this volume.
[2] *Verhandlungen des Vereins zur Beförderung des Gewerbfleisses*, 1879, vol. lviii., p. 31.
[3] See p. 244-246 of this volume.

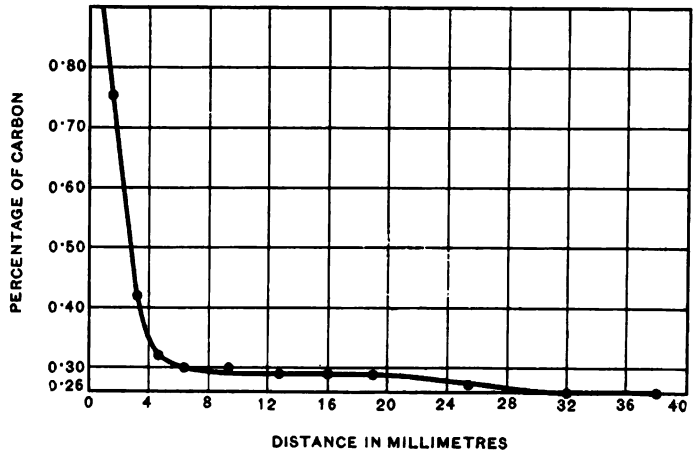
1865; Hempel, 1865; and Osmond quite recently. In my own experiment, pure electro-iron was carburised *in vacuo* at a temperature far below the melting point of iron, and under conditions which absolutely preclude the presence or influence of occluded gas. Osmond has shown (and some photographs illustrating the fact were exhibited) that when pure iron is carburised by the diamond, the iron is gradually penetrated by the carbon; and the question arises, at what rate does this penetration take place? There is not as yet much data which can be quoted in answer to this question; but the diagram (Plate XVII.) represents the carburisation of a steel rail already containing 0·26 per cent. of carbon, by the additional amount of carbon imparted to the metal during the course of the Harvey process. The time during which carburisation is effected is about 120 hours in the case of an armour-plate. The co-ordinates of the curve are respectively, *distance* to which the iron is penetrated by the carbon, and the *amount* of carbon which has so penetrated.

Now, if this curve be compared with one which represents the diffusion of common salt in water, or the diffusion of gold or platinum in solid lead, it will be found that the curve for the carburisation of iron resembles a true diffusion curve.

It would appear, therefore, to be very desirable, now that our whole scheme of naval defence depends so much on the carburisation of steel by the Harvey process, to work out the theory of carburisation which appears to present a simple case of the diffusion of solids.

Plate XVII.] [*To face page* 248.

DIFFUSION OF CARBON INTO IRON



BIBLIOGRAPHY.

PAPERS AND ADDRESSES BY THE LATE SIR WILLIAM ROBERTS-AUSTEN RELATING TO THE METALLURGY OF IRON AND STEEL.

1870. On the absorption of electro-deposited iron.—*Brit. Assoc. Report*, vol. xl., 1870, p. 62.

1881. Steel for the manufacture of dies.—*Chem. News*, vol. xliii., 1881, pp. 239-241. (Also Appendix to the *Eleventh Mint Report*.)

1881. Results of experiments made with a view to ascertain whether occluded gases play any part in the hardening and tempering of steel. *Inst. Mech. Engineers Proceedings*, 1881, pp. 706-711; *Physical Soc.*, 1881; and *Chem. News*, Jan. 17, 1881.

1883. On some theoretical considerations connected with the hardening and tempering of steel.—*Chem. News*, vol. xlvii., 1883, p. 195; and *Nature*, vol. xxvii., 1883.

1887. Electro-deposition of iron.—*Journ. Iron and Steel Inst.*, 1887, No. I.

1889. On the hardening and tempering of steel.—An Address to the British Association, 1889. (An exposition of M. Osmond's researches.)

1890. Carburisation of iron by the diamond.—*Journ. Iron and Steel Inst.*, 1890, No. I.

1896. Diffusion of carbon in iron.—*Journ. Iron and Steel Inst.*, 1896, No. I.

1898. Action of projectiles and the explosives on tubes of steel guns.—*Journ. Iron and Steel Inst.*, 1898, No. II; *Brit. Assoc. Report*, Toronto, 1897; and the *Times*, Aug. 23, 1897.

1899. The Fifth Report of the Alloys Research Committee.—*Proceedings Inst. Mech. Engineers*, 1899.

1899. Photomicrography of steel rails.—*Proceedings Inst. Civil Engineers*, 1899, pp. 36-38.

1899. Presidential Address to the Iron and Steel Institute.—*Journ. Iron and Steel Inst.*, 1899, No. I.

1899. On the nature of fracture of armour-plates.—*Fielden's Magazine*.

1900. Molecular unrest in solids.—*Proceedings Phil. Soc. of Glasgow*, April, 1900.

1900. Report on steel rails to the Board of Trade.—H.M. Stationery Office, 1900.

1900. Presidential Address to the Iron and Steel Institute.—*Journ. Iron and Steel Inst.*, 1900, No. II.

1902. Metallurgy in its relations to Engineering.—*Proceedings Inst. Civil Engineers*, vol. xix., p. 218.

REFERENCES TO ROBERTS-AUSTEN IN THE INDEXES TO THE JOURNALS OF THE IRON AND STEEL INSTITUTE (1869-1896) AND (1890-1900).

INDEX, 1869-1896.

INDEX, 1890–1900.

VI.

ROYAL SOCIETY PAPERS.

Freezing Point Curves—On the Liquation, Fusibility, and Density of Certain Alloys of Silver and Copper—On Certain Mechanical Properties of Metals considered in Relation to the Periodical Law—On the Structure of Metals, its Origin and Changes—On the Melting Points of the Gold-Aluminium Series of Alloys—On Surfusion in Metals and Alloys—On the Diffusion of Gold in Solid Lead at the Ordinary Temperature—Bibliography of Royal Society Papers.

In order to include within the limits of this volume some of Roberts-Austen's contributions to the Transactions and Proceedings of the Royal Society, it has been found necessary to condense portions of them, in order to avoid the repetition of matter which has been included in other sections.

The first paper contributed independently by Roberts-Austen to the Royal Society (in 1875) has been reproduced at some length, not for the sake of the actual results recorded (which have been modified by the more refined work of Heycock and Neville in later years), but in order to show how laborious the methods were by which any sort of approximation could be made to the melting points of metals and alloys before the introduction of modern pyrometric methods. The results obtained by these calorimetric methods and the approximation which they bear to results obtained in later years when the means of measurement had become so much more trustworthy, show how successfully Roberts-Austen employed these methods, which were subject to so many possible sources of error.

In 1897, more than twenty years later, he referred to this work when delivering one of a series of Cantor Lectures to the Society of Arts, of which the following is an abstract:—

"Rudberg was, I believe, the first to give measurements of the points of solidification of a series of associations of two metals which would enable a curve to be constructed; his work, however, only dealt with the easily fusible series of lead and tin alloys, the melting points of which were well within the range of the ordinary mercurial thermometer.

"I believe that a curve representing the points of solidification of the silver-copper series published 23 years ago by me in the *Proceedings of the Royal Society*[1] was the first which represented what is now justly called the 'freezing point curve' of a series which is beyond the range of the glass thermometer, and, therefore, demanded pyrometric work. The method adopted was very imperfect, for it consisted in transferring a ball of iron from the just molten alloy to a calorimeter. The curve, however, plotted from the results of the experiments truly revealed the nature of the alloys

[1] *Proc. Roy. Soc.*, vol. xxiii. (1874), p. 481.

under examination, and, viewed in the light of modern knowledge, the curve shows to which group of solutions the copper-silver series belongs. At that time the melting point of silver was taken to be 1,040° C., while that of copper was unknown, but was believed to be much higher than subsequent experiments have proved it to be. Nevertheless, if the results given in that paper of over twenty years ago be corrected to bring them into accordance with modern measurements of the freezing points of silver and of copper, it will be seen that the concordance is somewhat remarkable. The more important part of my old curve of 1874, corrected for the freezing point of silver which is now accepted, is, therefore, plotted in Fig. 1, together with the results recently obtained by Heycock and Neville,[1] whose very accurate determinations may be taken to be final. In both sets of results percentages by

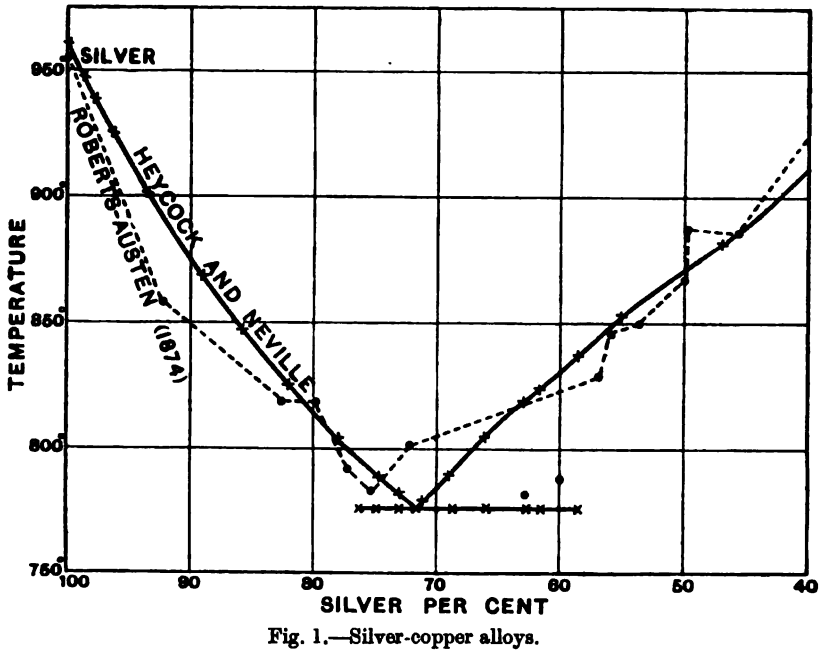


Fig. 1.—Silver-copper alloys.

weight of the constituent metals are given, and not atomic percentages. With reference to what is now called the *eutectic* alloy, that is the most fusible alloy of the series, the following statement was made by me in 1874 with reference to the alloys of silver and copper:—'I anticipated that Levol's homogeneous alloy, which contains 718·93 parts of silver in 1,000, would have the lowest melting point,' but the experimental results pointed to another alloy containing 630·3 of silver per thousand, as having a still lower melting point. It is evident that this result was due to the imperfections of the method which did not enable the last point at which the alloy remained fluid to be determined accurately, and this early inaccuracy was corrected in 1891, when almost the first experiments made with the recording pyrometer were

[1] *Phil. Trans. Royal Soc.*, vol. clxxxix. (1897), pp. 25-70.

devoted to a re-examination of the copper-silver series.[1] I showed that Levol's alloy appears to be the only one with a single freezing point, which points to its being the eutectic alloy of the series, but as there are theoretical reasons for considering that eutectics cannot be definite chemical compounds, and the composition of Levol's alloy corresponds accurately to the chemical formulæ, Ag_3Cu_2, I doubted whether it was really the eutectic alloy of the series, but any question as to whether Levol's alloy is the true eutectic of the silver-copper series has, since this lecture was delivered, been set at rest by M. Osmond,[2] who, by microscopic evidence, proved the alloy to have the banded 'pearly' structure of a eutectic alloy—that is, it possesses exactly the structure which a solidified 'mother liquor' should have. I am indebted to him for a photograph[3] of Levol's alloy which shows this beautiful pearly structure, and brings the eutectic of the silver-copper series into line with the 'pearlite' or striated portion of the structure, which represents the eutectic of the carbon-iron series of solutions.

"I have dwelt on these historical facts at some length because it was this old work, published by the Royal Society in 1874, which led my friend and colleague, Professor Guthrie, to examine the constitution of alloys in the course of a memorable research, which proved very fruitful in his skilful hands, as it enabled him to connect the *cryohydrates* of saline solutions with the *eutectics* in alloys."

The historical importance of this early work clearly justifies its reproduction in the following pages.

[1] "First Report to the Alloys Research Committee." *Proc. Inst. Mech. Eng.*, Oct. 1891.

[2] *Comptes Rendus*, vol. cxxiv. (1897), p. 1094.

[3] M. Osmond has since published this photograph in his admirable communication to the *Association internationale pour l'essai des materiaux*. Stockholm (1897).

ON THE LIQUATION, FUSIBILITY, AND DENSITY OF CERTAIN ALLOYS OF SILVER AND COPPER.

[*From the "Proceedings of the Royal Society,"* 1875, clxii., pp. 481-495.]

Alloys of silver and copper possess many curious chemical and physical properties which make them interesting apart from their economical value, and entitle them to careful investigation. The most remarkable of these is a molecular mobility, in virtue of which certain combinations of the constituents of a molten alloy become segregated from the mass, the homogeneous character of which is thereby destroyed.

These irregularities of composition have long been known. Some observations of Lazarus Erckern, in a work published in the seventeenth century,[1] show that he was familiar with them; that Jars possessed more accurate information on the subject is proved by his stating explicity, in a memoir published in 1781,[2] that in ingots of silver-copper alloys containing much of the base metal, the centre of the mass is less rich than the external portions.

The alloys in question have, during the present century, been the subject of many excellent researches in this country and on the Continent, the earliest systematic experiments being those of D'Arcet, Inspecteur Général des Essais at the French Mint, who in 1824 investigated the phenomena which attend the cooling of molten mixtures of silver and copper. He does not appear to have published his results; but in 1852 Levol stated, in a well-known memoir,[3] that the object D'Arcet had in view was the discovery of a method of rendering homogeneous the bars of metal used in coinage. He adds that the researches in this direction offered little prospect of obtaining such a result. I shall presently show, as the result of my experiments, that this conclusion may now be modified.

Levol, in his own experiments, cast the alloy to be examined either in a cubical iron mould of 45 mm. side, or in a sphere 50 mm. in diameter. He concluded that the only homogeneous alloy contains 718·93 parts of silver and 281·07 of copper in 1,000; and he considers this to be a definite combination of the two metals, having the formula Ag_3Cu_4 (or Ag_2Cu_2 if 63·34 be taken to be the equivalent of copper). All other alloys of silver and copper he views as mixtures of this definite alloy with excess of either of the metals.

In 1860[4] Matthiessen studied these alloys with the minute accuracy which characterised all his work, and he described them as "mechanical mixtures of allotropic modifications of the two metals in each other." The curve of electric conductivity led him to doubt Levol's conclusion that they were mixtures of the definite alloy Ag_3Cu_2 (new notation) with silver or copper; for, as he observes, if this were the case, we should expect to find that the curve consisted of two straight lines, connecting Levol's alloy with

[1] His work was translated in 1686 by Sir John Pettus. See *Fleta Minor*, Book I., p. 62.

[2] Voyages Métallurgiques, t. iii., p. 270.

[3] "Sur les alliages considérés sous le rapport de leur composition chimique." *Ann Chim. et Phys.* (3), t. xxxvi.

[4] *Phil. Trans.*, 1860, p. 173.

pure silver and copper respectively. But on examining the curve, starting from the copper side of it, we see that a rapid decrement in conducting power is caused by copper being alloyed with a small quantity of silver. From the alloy containing 10 per cent. of silver to that containing 65 per cent. we have a straight line; and we may regard the intermediate alloys as mixtures or solutions of these two alloys. Again, from the latter of these to that containing 72 per cent. of silver, we may have a mixture or solution of alloys containing 65 and 72 per cent. respectively. This last point (which corresponds to a conducting power of 63·7, fine silver being taken as 100) is the minimum point of the curve, and corresponds almost exactly to Levol's Ag_3Cu_2 alloy. The alloys intermediate between this and pure silver may be mixtures, or perhaps solutions of it in silver containing a small quantity of copper. Now it would appear as if there was an alloy of constant composition at about the point which represents the one containing 65 per cent. of silver; otherwise we should expect a straight line from the alloy containing 72 per cent. of silver to that which contains only 10 per cent.

I now proceed to give the results of my own experiments.

In commencing the inquiry, it seemed probable that, by determining the melting points of a series of the alloys of silver and copper, information of much interest might be gained as to the arrangement which attends the solidification of a fluid mass of these metals. I adopted a modification of the plan described by Pouillet,[1] and employed by him in determining the specific heat of platinum at high temperatures.

As soon as the alloy under examination was melted, a wrought-iron cylinder of known weight was dropped into it by means of a wire support. The crucible was them removed from the furnace, and, when the alloy showed signs of solidifying, the iron was transferred to a calorimeter, which consisted of two concentric vessels of thin polished brass, such as is ordinarily used for determining specific heats by the methods of mixtures.

It was necessary to determine the mean specific heat of the iron employed, between 0° C. and a known fixed point near the maximum temperature likely to be attained in the course of the experiments. The melting point of silver was a convenient one, and it has been accurately ascertained by M. Becquerel,[2] who placed a wire of pure silver in a crucible which was enclosed in a porcelain tube surrounded by the vapour of boiling zinc, the temperature of which has been fixed by M. Deville at 1,040° C.[3] As the heat was sufficient to partially fuse the silver, this temperature may safely be taken as the melting point of the metal.

In order, therefore, to determine the specific heat of the iron, I plunged the cylinder into molten silver, and transferred it to the calorimeter. I may here observe that the film of oxide which formed on the surface of the iron to a great extent protected it from being attacked by the molten alloy; but it was impossible to avoid carrying into the calorimeter a small quantity of metal which adhered to the iron. The metal so introduced was always collected and allowed for. With pure silver 0·05701 was taken as the specific

[1] Eléments de Physique, sixième édition, t. ii., p. 564.
[2] *Ann. Chim. et Phys.* (3), t. lxviii., p. 74.
[3] *Comptes Rendus*, t. lvii., p. 897.

heat, while in the case of alloys the necessary correction was made by deducting the specific heat of each alloy from the specific heats of its constituents; and the equivalent weight of iron was calculated by multiplying the weight of introduced metal by its specific heat and dividing this product by the specific heat of iron as ascertained by preliminary experiments. The weight was then added to that of the iron employed.

The specific heats of metals at high temperatures have not been determined, and the adoption of Regnault's numbers in calculating the heat carried into the calorimeter by the alloys may tend to mak the results a few degrees too high.

The results of the experiments were calculated by means of the following formula:—

$$x = \frac{(P + p_{,}c_{,} + p_{,,}c_{,,})(\theta - t)}{p(T - \theta)},$$

where p is the weight of the iron employed.
P " " water.
$p_{,}c_{,}$ and $p_{,,}c_{,,}$ are the water-equivalents of the calorimeter and thermometers respectively.
T is the initial temperature of the iron.
t " " " " water.
θ " final temperature.
x " specific heat required.

In one experiment these quantities had the following values:—

p =	83·140 grammes.	T =	1,040° C.
P =	260·520 "	t =	16° C.
$p_{,}c_{,} + p_{,,}c_{,,}$ =	15·687 "	θ =	63° C.

The weight of silver carried over was 3·266 grammes, the heating effect of which is equivalent to that of 1·306 grammes of iron. Therefore, the corrected value of p is 83·140 + 1·306 = 84·446 grammes.

Substituting these values in the above equation,

$$x = \frac{(260{\cdot}52 + 15{\cdot}687)(63 - 16)}{84{\cdot}446\,(1{,}040 - 63)}$$
$$= {\cdot}15734.$$

Three successive experiments gave

·15795,
·15550,
·15734,
the mean ·15693 being finally adopted.[1]

[1] Weinhold gives 0·1567 as the mean specific heat of wrought iron between 0° and 900° C. (*Pogg. Ann.*, vol. cxlix., p. 214).

It may be pointed out that the specific heat of iron as thus determined includes and neutralises several errors which are incidental to this method of determining high temperatures. The principal of these are :—(1) The loss of heat, which is rendered latent by the small amount of water which is evaporated ; (2) the slight difference between the specific heat of the iron and the specific heat of the oxide formed on its surface ; (3) the loss of heat sustained by the iron during its transfer from the crucible to the calorimeter ; and (4) the radiation from this instrument.

The melting point of copper has not been exactly ascertained ; and I experienced great difficulty in determining it by means of the calorimeter, as the molten metal adheres tenaciously to the iron. Accuracy on this point is not absolutely essential to this inquiry, and I, therefore, adopted 1,330° C., as this is considered by Dr. Van Riemsdijk [1] to be the probable melting point of pure copper.

The several alloys were synthetically prepared by melting together pure silver and pure copper ; and as soon as the crucible containing the fused metal was withdrawn from the furnace, a small portion of the thoroughly stirred alloy was granulated and set aside for analysis.

The requisite data for ascertaining the melting point of each alloy were furnished by an experiment similar to that which was made for determining the specific heat of the iron, and in calculating the result it was only necessary to transpose the equation already given, T being the unknown quantity instead of x. The formula then becomes

$$T = \frac{(P + p_{,}c_{,} + p_{,,}c_{,,})(\theta - t)}{p\,x} + \theta,$$

the value assigned to x being in all cases 0·15693, the mean specific heat of iron, as given above.

To take an example. In one experiment to determine the melting point of the 820·7 alloy, the following values were obtained :—

$$P = 247{\cdot}74 \text{ grammes.} \qquad t = 15^\circ \text{ C.}$$
$$p_{,}c_{,} + p_{,,}c_{,,} = 15{\cdot}687 \quad ,, \qquad \theta = 56^\circ \text{ C.}$$
$$p = 82{\cdot}55 \quad ,,$$

The weight of alloy carried over was 3·608 grammes, the heating effect of which was equivalent to that of 1·543 grammes of iron. Therefore, the corrected value of p is

$$82{\cdot}55 + 1{\cdot}543 \text{ grammes} = 84{\cdot}093 \text{ grammes.}$$

Substituting these values in the above equation,

$$T = \frac{(247{\cdot}74 + 15{\cdot}687)(56 - 15)}{84{\cdot}093 \times {\cdot}15693} + 56$$
$$= 874{\cdot}42^\circ \text{ C.}$$

The results of the experiments are given in the following table :—

[1] *Archives Néerlandaises*, t. iii. (1868).

Melting Points of Silver-Copper Alloys.*

No.	Parts of pure silver in 1,000 parts of the alloy.	Approximate formula.	Melting-points, in degrees Centigrade.	
			Observed.	Mean.
1	1,000 (pure silver)	..	..	1040
2	925	Ag_7Cu	919·9 939·0 934·5	931·1
3	820·7	Ag_3Cu	874·6 891·8 900·5 877·8	886·2
4*	798	Ag_5Cu_2	882·4 885·4 889·5 890·9	887·0
5*	773·6	Ag_2Cu	854·9 857·9 862·3	858·3
6*	750·3	Ag_7Cu_4	852·3 848·5	850·4
7	718·93	Ag_3Cu_2	868·4 863·5 879·5	870·5
8	630·29	AgCu	851·9 844·9 837·6 852·7	846·8
9	600	Ag_7Cu_8	854·9 849·8 858·6 864·6	857·0
10*	569·6	Ag_7Cu_9	897·6 902·2	899·9
11*	561·1	Ag_3Cu_4	910·8 914·8 927·2	917·6
12*	540·8	$Ag_{20}Cu_{29}$	914·1 916·0 921·5 927·6	919·8

* These results are reproduced in order to show the concordance of the figures obtained in successive experiments. To bring them into line with modern work it is necessary, of course, to adopt the figures which are now accepted as the melting points of silver and copper.

No.	Parts of pure silver in 1,000 parts of the alloy.	Approximate formula.	Melting-points, in degrees Centigrade.	
			Observed.	Mean.
13*	500	Ag_3Cu_5	931·9 944·1 945·6	940·8
14	497	$Ag_{15}Cu_{26}$	940·2 973·0 981·5 955·6	962·6
15*	459·4	$AgCu_2$	953·5 963·9 964·1	960·8
16	250·5	$AgCu_5$	1080·8 1141·8 1114·9 1119·1	1114·1
17	0 (pure copper)	..	..	1330

[These melting points were graphically represented by an accompanying curve, the co-ordinates being the amounts of silver in the several alloys and their melting points. See Fig. 1, and the remarks on pp. 253-254.]

The curve exhibits a somewhat rapid decrement from pure silver to the alloy, which contains 925 parts of silver, the one employed for the British silver coins. In it the relation between the amounts of metals present is approximately represented by the formula Ag_7Cu.

The alloys numbered 7 and 8 are of singular interest. The first, which contains 718·93 parts of silver, is Levol's homogeneous alloy; and I anticipated that it would have the lowest melting point; but the results showed that the alloy containing 630·29 parts of silver (No. 8) melts at a point which is 23·7° lower. In this alloy a very simple relation exists between the atoms of the constituent metals, the formula being AgCu. Additional interest is imparted to it by Matthiessen's curve of electric conductivity having shown that the arrangement of an alloy of this composition would probably be peculiar. From this point the curve passes through the points representing alloys in which base metal predominates to the melting point of pure copper.

Further evidence as to the melting points of Nos. 7 and 8 was afforded by placing strips of them in small covered crucibles surrounded by the vapour of boiling cadmium, the temperature of which has been fixed by Deville at 860° C. Both alloys melted, the first partially, the second completely. I am convinced, therefore, that the melting points of the alloys generally are not inaccurately indicated by the curve. It is, however, not improbable that the examination of a more extended series of alloys may point to the necessity of slightly modifying its form. This critical examination is especially necessary in the region of the 497 alloy; for not only do the results obtained on it

diverge widely among themselves, but their mean is far removed from the probable line of the curve.

I am not satisfied with the results I have obtained on an alloy which contains 773·2 parts of silver. This alloy is of special interest; its formula is $Ag_2'Cu''$, silver being monatomic.

[Since the above was submitted to the Royal Society, I have made additional experiments on alloys in these two portions of the curve. The calorimeter used was of thin polished silver, capable of holding 1,200 grammes of water, which were never raised through more than 15° C. The water equivalent of the instrument was only 15·72 grammes. The masses of iron used were such as had been employed as carriers of heat in the first experiments: the mean of several very concordant results gave ·15003 as the specific heat of the iron when this new calorimeter is employed; and, as has already been pointed out, this number includes and neutralises several errors.

The results are distinguished by an asterisk in the table, and have been added to those originally indicated in the diagram. They confirm the direction originally given to the curve in the region of the alloys which contain from 718 to 800 parts of silver; but the existence of a cusp has been detected at the point which represents the alloy No. 11 (Ag_3Cu_4). It may be interesting to point out that the results from which Matthiessen's curve of electric conductivity was developed appear to prove the presence of a cusp at the point which represents the alloy 459·4 ($AgCu_2$).—15*th May*, 1875.]

It may be useful to compare these results with those obtained by Rudberg on alloys of lead and tin. He found that when a thermometer is placed in a molten alloy of these metals two distinct stationary points are indicated during the passage from the liquid to the solid state. One of these points is always 187° C.; and in the alloy $PbSn_6$ the two points coincide at this temperature—a fact which led Rudberg to conclude that it was the only alloy in which the whole of the metals were chemically combined. I hope, in continuing this inquiry, to be able to ascertain whether the change of state in the case of silver-copper alloys also terminates at a constant temperature. I may mention that M. A. Rich [1] determined the melting points of certain alloys of tin and copper by means of Becquerel's thermo-electric pyrometer; and he obtained concordant results with the alloys $SnCu_3$ and $SnCu_4$; but with all other alloys the results differed widely among themselves.

It is at present difficult to show the direct bearing of these results on the phenomena of liquation in alloys of silver and copper; but the curve is valuable, as it proves that the alloys Nos. 7 and 8 occupy positions in the lower portions of the curve similar to those which they hold on Matthiessen's curve of electric conductivity.

The range of temperature which these melting points exhibit appears to justify the conclusion that liquation is in some way the result of the unequal cooling of a mass of silver and copper, and that if the cooling could be greatly protracted the liquation would be considerably modified. In order to ascertain whether this were the case, I used cubical moulds (about 45 mm. side) of firebrick, which were easily heated to bright redness, and in which the alloys

[1] *Ann. Chim. et Phys.*, t. xxx., p. 351.

could be *slowly* and *uniformly* cooled.[1] (The paper was illustrated by drawings of a number of such cubes, and the liquation of the constituents was indicated.)

All the cubes were cast in moulds of this description. The first of these, the composition of which was about 925 parts of silver per 1,000 of the alloy, was cooled rapidly. Its structure confirms Levol's general conclusion, as the centre contains 12·8 parts per thousand more silver than the external portions. On the other hand, when the same alloy is slowly cooled the constituents hardly undergo any molecular re-arrangement, the maximum difference being only 1·4 per thousand. A cube of the alloy used for the French coinage, when rapidly cooled, exhibits a difference of 10·1 parts per thousand between the centre and the corners; but when the same metal is slowly cooled the variation is only 1·3 parts per thousand. The maximum difference found by Levol in his homogeneous alloy was 0·44 part per thousand. I find that if the cooling is slowly effected this homogeneity is disturbed, the external portions being slightly richer in silver than the centre. Another cube exhibits the results of an experiment on the alloy which has the lowest melting point and the simple chemical formula AgCu. Its structure is interesting, as the action of gravity appears to have influenced the arrangement, the lower parts of the cube being richer than the upper. The maximum difference is 21·1 parts per thousand. I should observe that Levol found the corners of a cube of this alloy to be 15 parts richer than the centre; but the only alloy in which he detected any effect of gravity was that containing 690 parts of silver. Another cube shows the results of analyses on the different portions of a mass of the alloy containing 333·3 parts of silver per thousand ($AgCu_4$). The mass varies in composition, but the arrangement does not appear to have been guided by any law.

The inquiry appears to show that several alloys of silver and copper are, under suitable conditions, as homogeneous as Levol's alloy, the chief peculiarity of which consists in its not being liable to liquation when poured into a mould at the ordinary temperature and cooled rapidly.

It will be remembered that experiments prove that in all alloys which contain less than 71·89 per cent. of silver the external parts are richer than the centre. The curve of fusibility shows that the alloys which contain less than 35 per cent. of silver have higher melting points than other alloys of silver and copper, or even than pure silver. It would not appear, therefore, that liquation is the falling out of the least fusible alloy present in a mass of silver and copper; for if it were, the external portions of the alloys would in all cases be less rich in silver than the centre.

I cannot at this stage of the inquiry offer a complete explanation of this molecular re-arrangement; but I venture to think that the results already obtained are interesting. They show, first, that the same alloys are situated

[1] In treating of ingots of low standard, Jars stated in 1781, in the work to which I have already alluded:—"Je remarquai par des expériences que pour rendre les lingots d'une teneur plus égale dans toutes les parties il falloit que les lingotières fussent aussi chaudes qu'il est possible." I should state that certain unpublished experiments by Dr. Boycott, formerly Assay Master in the Calcutta Mint, have shown that the liquation of silver-copper alloys is modified by casting the metal in sand moulds, and that Mr. E. Seyd suggested in 1871, in a work printed for private circulation, the use of hot iron moulds in casting gold and silver, as an improvement in the process of coinage, the bars being "more equal in temper and in molecular arrangement" (patented in 1872, No. 368).

on the turning points of the curves of fusibility and electric conductivity; and second, that the arrangement of an alloy is to a great extent dependent on the rate at which it is cooled.

In accordance with a suggestion made to me by Mr. R. Mallet, I have endeavoured to determine the relation between the densities of silver in the solid and the molten state. I adopted the method which he devised and has employed in the determination of the density of molten cast iron.[1]

A conical vessel of best thin Low-Moor plate (1 mm. thick), about 16 cm. in height, and having an internal volume of about 540 c.c. was weighed, first empty, and subsequently when filled with distilled water at a known temperature. The necessary data were thus afforded for accurately determining its capacity at the temperature of the air. Molten silver was then poured into it, the temperature at the time of pouring being ascertained by the calorimetric method already described. The precautions, as regards filling, pointed out by Mr. Mallet were adopted; and as soon as the metal was quite cold, the cone with its contents was again weighed.

The surface of the molten metal in the crucible was covered with charcoal; and as pure silver, when in a liquid state, is known to absorb oxygen if exposed to the air, the cone was filled with an atmosphere of coal gas.

The most important of the corrections applied to these results was that for change of volume of the iron vessel which attended the introduction of the molten metal.

Different qualities of wrought iron vary considerably as to dilatation by heat. This fact, together with the known increase in the expansion at high temperatures, rendered it necessary to determine the mean coefficient between 0° C. and the melting point of silver. For this purpose a modification of Ramsden's method was adopted, the iron being placed in a graphite trough and surrounded by molten silver. The micrometer reading was taken when the length of the iron remained for a short period invariable, as this was the true solidifying point of the silver, the loss of the latent heat of liquefaction rendering the temperature constant.

A great number of experiments were made; and although they were attended with much difficulty, I believe the following results to be trustworthy (the numbers represent the mean coefficient of linear expansion per 1° C. of the Low-Moor iron employed, up to the temperature of melting silver):—

	·00001242,
	·00001254,
	·00001215,
	·00001219,
	·00001271,
Mean, . .	·00001240,

which gives a mean coefficient of cubical expansion

·00003720.

This result is considerably higher than that of Rinmann, who gives 0·00002808 as the mean coefficient of cubical expansion of wrought iron between 15° C. and "a white or welding heat."

[1] *Proc. Roy. Soc.*, vol. xxii., p. 366, and vol. xxiii., p. 209.

The results of the experiments made with a view to ascertain the densities of pure silver and of Levol's homogeneous alloy when in a molten state are given in the accompanying table. This alloy was chosen for the experiment, as its density when solid very nearly agrees with that calculated from the densities of the constituent metals.

The cubic dilatation was, in the case of pure silver, in the ratio of 9·4612 : 10·57. Deducting from this the mean coefficient through, say, 1,050° C., we obtain

0·00011164 per 1° C.

The coefficient of linear expansion was, therefore,

0·00003721.

The mean of the coefficients of linear dilatation of silver between 0° and 100° C., given by various authorities, is

0·00002015.

It will thus be seen that the expansion of silver between 0° C. and 1,050° C. is about twice as much as it would have been had this rate of expansion been maintained through the whole range of temperature.

The mean coefficient of linear dilatation of Levol's alloy, as deduced from the results given in the table, is

0·00003703;

but it is impossible to compare this with the rate of expansion at low temperatures, as the latter has not been ascertained.

	Initial volume of cone.	Volume of cone filled with molten metal.	Temperature of metal when poured.	Weight of metal.	Density when fluid.	Density of solid metal.
	c.c.	c.c.	° C.	grms.		
Pure silver.	536·6	556·3	1,143	5255·4	9·4468	10·57
	542·9	564·4	1,223	5348·3	9·4757	
	Mean, ...				9·4612	
Levol's alloy.	735·13	778·06	1,020	7062·4	9·0788	9·9045 (Levol), 9·998 by calculation.
	537·42	557·25	1,131	5033·4	9·0321	
	Mean, ...				9·0554	

In conclusion, I have much pleasure in acknowledging the assistance I have received from one of the Assistant Assayers at the Royal Mint, Mr. Edward Rigg, whose co-operation has been of much service to me; and I must also express my thanks to Joseph Groves, Senior Fireman, who aided me in the furnace operations.

[This work on the fluid densities of metals was continued in collaboration with Sir Thomas Wrightson, and formed the subject of two papers which were read before the Physical Society in 1881 and 1882, and published in the *Philosophical Magazine* for April, 1881, and May, 1882, respectively.]

[The two papers which follow embody in a brief form the amount of progress which Roberts-Austen had made, in the years preceding 1891, towards a knowledge of the constitution and behaviour of alloys during melting and solidification. The second paper included the first description given of the autographic recording pyrometer.]

ON CERTAIN MECHANICAL PROPERTIES OF METALS CONSIDERED IN RELATION TO THE PERIODIC LAW.

[*From the "Philosophical Transactions of the Royal Society,"* 1888, vol. clxxix., pp. 339-349.]

The influence exerted by a small quantity of metallic or other impurity on a mass of metal is shown by a remarkable series of phenomena, the nature of which has hitherto been but little studied, although the effect produced by the presence of such added matter is widely recognised by metallurgists. There are many cases in which a small quantity of impurity has so entirely altered the appearance and the physical properties of a metal as to lead, in the absence of other evidence, to its being mistaken for a distinct elemental substance. The valuable mechanical properties conferred upon metals by associating them with small, but definite, amounts of other metals constitute the main reason why metals devoted to industrial use are seldom employed in a state of purity. A familiar instance of the influence of a small quantity of a metalloid on a mass of metal is presented by the extraordinary change in the properties of pure iron which attends the introduction into the metal of a small quantity of carbon. There is no fact in metallurgy of which the importance is more widely recognised, and when Bergman,[1] in 1781, experimentally demonstrated that the differences between pure iron, steel, and cast iron depend on the presence or absence of carbon, he expressed his astonishment at the smallness of the amount of carbon capable of producing such effects, and he stated that the explanation of the phenomenon presented a "difficulty of difficulties"; and the problem has certainly not been solved in the century which has elapsed since Bergman wrote.

In other directions the evidence as to the importance of the action of traces of impurity is just as strong. This is indicated by the fact, referred to by Sir Hussey Vivian,[2] that "one thousandth part of antimony converts first-rate 'best selected' copper into the worst conceivable," and by the observation of Mr. Preece,[3] that "a submarine cable made of the copper of to-day," the necessity for employing pure metal being recognised, "will carry twice the number of messages that a similar cable of copper would in 1858," when less importance was attached to the presence of foreign matter in the copper. It may be well to refer to a but little known case in which the change in the structure of a metal produced by the presence of a minute quantity of foreign matter becomes at once evident by comparing the fractured surfaces of the pure and impure masses. Bismuth, when pure, has a fracture which shows large brilliant mirror-like crystalline planes; but, if only the

[1] "De Analysi Ferri, Opuscula Physica et Chemica," by Torbern Bergman, vol. iii., 1783: or *French translation* (from the Swedish): "Analyse du Fer," by M. Grignon, Paris, 1783.

[2] Lecture delivered at Swansea in 1880.

[3] *Instit. Civil Engineers Trans.*, vol. lxxv., part 1, 1883.

$\frac{1}{1000}$ part of tellurium be present, the fracture is, as a specimen submitted to the Society showed, entirely different, being minutely crystalline and lighter in colour than pure bismuth.

The mode of action of these small quantities of impurity is still very obscure, but it should be remembered that Prof. W. Spring, of Liége, has recently given evidence [1] in favour of the view that molecular polymerisation may take place even in a *solidified* alloy, and Matthiessen,[2] in a classical series of researches on the electrical resistance of alloys, communicated to this Society nearly thirty years since, was led to the view that in many cases the constituent metals of alloys exist in the form of allotropic modifications, the quantities of the metal producing a rapid decrement in conductivity being too small to enable the effect to be explained by attributing it to the formation of chemical compounds.

In the present paper, attention is directed to the way in which the tenacity and extensibility of metals may be affected by small quantities of metals and metalloids, with the view of showing that the relations between these small quantities of the elements and the masses of metal in which they are hidden are under the control of the law of periodicity, which, as originally expressed, states that "the properties of the elements are a periodic function of their atomic weights." Carnelley [3] has set forth at some length the reasons for supplementing the law as follows:—"The properties of the *compounds* of the elements are a periodic function of the atomic weights of their constituent elements"; and the question arises, may the law be so extended as to govern the relations between the constituent metals of alloys, in which, as is well known, the atomic proportions are often far from simple.

The influence of a small quantity of one metal on another is so marked that it appeared well to approach the consideration of the problem by investigating the nature of the change so effected in the mechanical properties of metals. Gold was the metal selected as a basis for the experiments, mainly because it can be more readily brought to a high degree of purity than any other metal: the accuracy of the results of the experiments are not likely to be disturbed by the oxidation of the gold or by the presence of occluded gases: it possesses considerable ductility and tenacity; and the amount of the metallic or other impurity added to the precious metal can be determined with rigorous accuracy. With the exception of iron, gold has received more attention than any other metal in relation to the effects of impurities upon it, and much information upon the subject is scattered through the works of the older chemists; but the first systematic experiments were made, by the direction of the Lords of the Committee of Privy Council, by Mr. Hatchett in 1803, who endeavoured to ascertain "the chemical effects produced on gold by different metallic substances when employed in certain proportions as alloys." He obtained results of great interest, which were communicated to the Royal Society [4]; but in his time the importance of submitting metals to mechanical tests was not appreciated; his observations were thus mainly directed to ascertaining whether gold is rendered hard and

[1] *Bull. de l'Acad. Roy. de Belgique*, vol. xi., 1886.
[2] *Phil. Trans.*, vol. cl., 1860, p. 85; and vol. cliv., 1864, p. 167
[3] *Phil. Mag.*, vol. viii., 1879, p. 368.
[4] *Phil. Trans.*, 1803, part 1, p. 43

brittle by the presence of foreign metals. The gold he employed was only of commercial purity, and he specially examined the effect of impurities on the *standard* gold used for coinage, which contains 916·7 parts of pure gold and 83·3 of copper per 1,000 parts. He showed, by means of bending and hammering the gold, that small quantities of certain metals render it very brittle, and he concluded that "the different metallic substances which have been employed in the present experiments appear to affect gold nearly in the following decreasing order :—

1. Bismuth. } These are nearly equal in effect.
2. Lead. }
3. Antimony. }
4. Arsenic.
5. Zinc.
6. Cobalt.
7. Manganese.
8. Nickel.
9. Tin.
10. Iron.
11. Platinum.
12. Copper.
13. Silver."

In 1886, in a lecture delivered at the Royal Institution,[1] I pointed out that standard gold breaks with a load of 18 tons to the square inch, and elongates 34 per cent. before breaking. If the standard gold has only $\frac{1}{2000}$ part of lead added to it, it becomes very fragile, and breaks with a stress of about $5\frac{1}{2}$ tons to the square inch, instead of the 18 tons borne originally. It is remarkable that $\frac{1}{100}$ part of lead added to gold does not appear to diminish its tenacity more than $\frac{1}{2000}$ part. Prof. Kennedy has kindly made further experiments on pure gold to which $\frac{1}{500}$ part of lead had been added; and his results substantially confirm those just referred to, for he found that the breaking load of the contaminated gold was 1·84 tons per square inch, and the elongation unmeasurable.

In the experiments which follow, pure gold was in all cases melted under a pure form of charcoal; a certain amount of the metallic impurity to be added was carefully weighed, on a delicate assay balance, and tightly wrapped in pure gold foil. This little packet was held in a charred splinter of wood, and rapidly submerged in the molten gold. It was found better not to stir the gold, but to thoroughly mix the contents of the crucible by giving it a swinging motion. The gold was then poured through an atmosphere of coal gas into an iron mould lined with lamp black, and the resulting bars had the following dimensions :—3·5 inches length, 0·295 inch breadth, 0·205 inch thickness, the sectional area of the bars being, therefore, 0·0605 square inch. The length varied in some cases. The results of analyses of different parts of the bars showed that the mixing had rarely been defective, but there was evidence in some cases that liquation had disturbed the homogeneity of the metal, though not to any serious extent.

[1] Roberts-Austen, *Roy. Inst. Proc.*, 1886; and *Engineering*, May 28, 1886; also pp. 313-323 of this volume.

The test pieces were made in the Assay Department of the Royal Mint, by Mr. Groves, whose careful manipulation and great experience in melting the precious metals were of much service to me.

In the case of very volatile metals, such as potassium and cadmium, a rich alloy with gold was first prepared by fusion in an atmosphere of pure hydrogen. The alloy so formed was analysed, and the necessary amount of it added to pure gold in the manner already described, so as to give approximately $\frac{2}{10}$ per cent. of foreign metal in the solidified mass. It may here be pointed out that the purity of the gold employed had been well established by careful comparison with gold purified by myself in 1873 [1] for use as Trial Plates in connection with the coinage of this country,[2] the purity of which has been recognised by no less an authority than M. Stas. The amount of foreign matter added to the gold could, therefore, be readily ascertained with minute accuracy by the ordinary method of assay, except in the case of metals of the platinum group. It should be observed, however, that the method of assay, which consists in eliminating impurities and in comparing the weight of the purified gold with that of the portion of metal taken for assay, does not enable the assayer to distinguish whether an impurity is metallic or a metallic oxide. However carefully the experiments were conducted, it was at times found impossible to prevent the small amount of added metal from being oxidised to a certain extent during the casting of the bars. The error thus occasioned is believed to be but small, and was proved not to be serious in the case of those metals whose oxides can be reduced by hydrogen, by laminating or breaking in fragments the portion of metal to be submitted to assay and heating it to bright redness in a stream of pure and dry hydrogen.

The testing machine used in the following experiments belongs to the Metallurgical Laboratory of the Royal School of Mines, and is of the form devised by Prof. Gollner, and used by himself at Prague, and by Prof. Böck at Leoben. It is a double lever vertical machine, adapted only for testing short pieces of metal, and working up to a stress of 20 tons.[3] The pieces of metal tested were not provided, as they should have been, with enlarged, ends, but they nevertheless seldom broke within the jaws of the machine, and when they did the result was rejected.

The purest gold attainable has a tenacity of 7·00 tons per square inch, and an elongation of 30·8 per cent. Prof. Kennedy found that a less pure sample, which contained 999·87 parts of fine gold in 1,000, broke with a load of 6·29 tons per square inch, and elongated 18·5 per cent. before breaking.

In selecting tenacity as the property to be tested with a view to ascertain the effect of the added matter, the following considerations presented themselves :—

Prof. Spring has built up alloys by compressing the powders of the constituent metals ; and, by pointing to the evidence of molecular mobility in solid alloys, he has done much to show the close connection which exists between cohesion and chemical affinity. Raoul Pictet has concluded that

[1] *Chem. Soc. Journ.*, vol. xxvii., 1874, p. 197.

[2] Cantor Lectures, *Soc. Arts Journ.*, vol. xxxii., 1884, and pp. 29-66 of this volume.

[3] This machine is described by Professor Kennedy, F.R.S., *Instit. Civil Engineers Proc.*, vol. lxxxviii., 1886-87, part 2.

there is an intimate relation between the melting points of metals and the lengths of their molecular oscillations, the length of the oscillations diminishing as the melting point increases, and, as Carnelley has pointed out, "we should expect that those metals which have the highest melting points would also be the most tenacious." It is known that the melting points of metals are altered by the presence of small quantities of foreign matter; their cohesion is also thereby altered: the degree of cohesion may thus be investigated either by change of temperature or by mechanical stress, being, as it is, some function of each of these. It might have been well to ascertain the amount of change in the melting point of gold produced by the presence of different elements in small quantity, but, unfortunately, slight variations in high melting points are very difficult to determine with any approach to accuracy, and it appeared to be better to ascertain the effect of metallic and other impurity on the cohesion of the gold as indicated by the amount of force externally applied in an ordinary testing machine, and in that way to ascertain whether the effect of added metals is amenable to any known law.

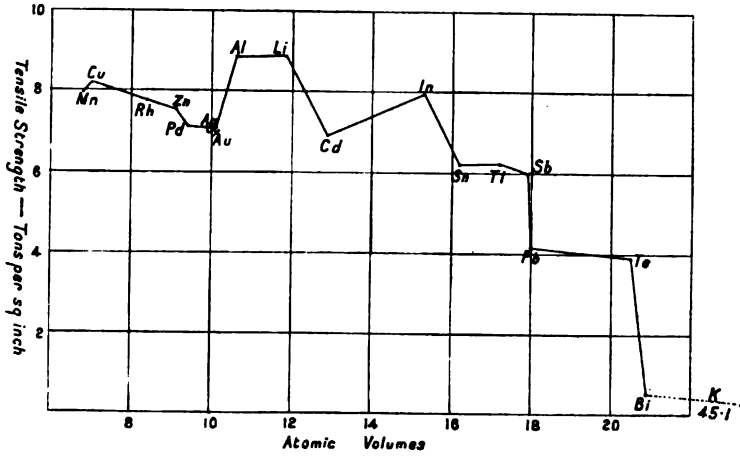
In the following experiments only the purest gold I could prepare was employed. It broke with a load of 7·00 tons per square inch, and elongated 30·8 per cent. (on 3 inches) before it fractured, as recorded in the diagrams (Plate XVIII.) subsequently referred to. The effect on the tenacity of gold produced by adding to it about $\frac{2}{10}$ per cent. of various metals and metalloids is shown in the following table, in which the results are arranged according to the tensile strengths:—

Name of added element.	Tensile strength.	Elongation, per cent. (on 3 inches).	Impurity, per cent.	Atomic volume of impurity.	Reduction of area at fracture, per cent.
	Tons per sq. in.				
Potassium, .	Less than 0·5	Not perceptible	Less than 0·2	45·1	Nil.
Bismuth, .	0·5 (about)	,,	0·210	20·9	,,
Tellurium, .	3·88	,,	0·186	20·5	,,
Lead, . .	4·17	4·9	0·240	18·0	Very slight
Thallium, .	6·21	8·6	0·193	17·2	15
Tin, . .	6·21	12·3	0·196	16·2	Not measured
Antimony, .	6·0 (about)	qy.	0·203	17·9	54
Cadmium, .	6·88	44·0	0·202	12·9	See note [2]
Silver, .	7·10	33·3	0·200	10·1	,,
Palladium, .	7·10	32·6	0·205	9·4	75
Zinc, . .	7·54	28·4	0·205	9·1	74
Rhodium, .	7·76	25·0	0·21 (about)	8·4	See note [2]
Manganese, .	7·99	29·7	0·207	6·8	60
Indium, .	7·99	26·5	0·290	15·3	72
Copper, .	8·22	43·5	0·193	7·0	See note [2]
Lithium, .	8·87	21·0	0·201	11·8	60
Aluminium, .	8·87	25·5	0·186	10·6 [1]	46

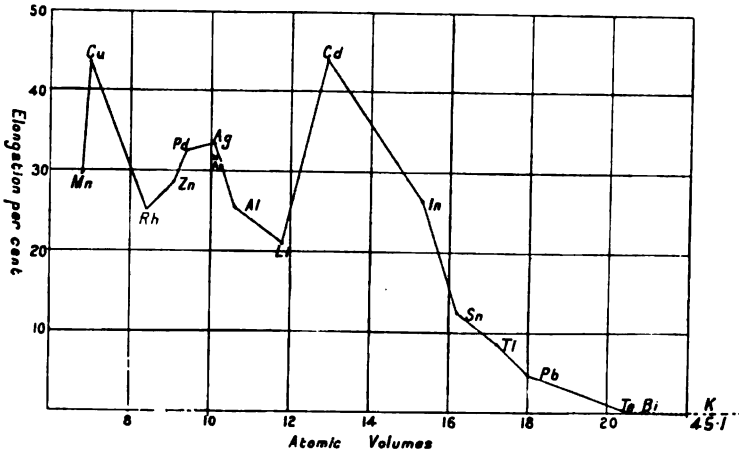
The figures given in the fourth column show that there is some divergence in the amounts of impurity added to the gold. That this is not of much

[1] This is the value given by Lothar Meyer. Mallett's determination of the density of pure aluminium would give 10·45.

[2] These test pieces drew out after the manner of pitch—that is, as a viscous solid.—August 4, 1888.



Tensile Strength and Atomic Volumes.



Elongation and Atomic Volumes.

importance in these preliminary experiments may be inferred from the fact, already mentioned (on p. 268), that the $\frac{1}{2000}$ part of lead appears to produce nearly the same diminution in tenacity as the $\frac{1}{500}$ part; a mere trace of certain metals, moreover, will greatly diminish the tenacity of gold.

[The results were also graphically represented in accompanying diagrams, Plate XVIII.] The tests were made with great care by Dr. E. J. Ball, Assistant in the Metallurgical Laboratory of the Royal School of Mines.

It will be evident, from the figures given in the table, that certain mechanical properties of gold are greatly affected by the addition, in small quantities, of potassium, bismuth, tellurium, and lead, while other metals, such for instance as silver and palladium, hardly produce an alteration. The change in the structure of the precious metal is, in some cases, very remarkable as drawings submitted to the Society showed. Pure gold has a silky fracture, while gold containing the $\frac{1}{500}$ part of lead, tellurium, bismuth, or antimony shows a well-developed crystalline structure, the crystalline planes diverging from a line in the centre of the fractured bar. The character of the fracture does not appear to be closely related to that of the added metal, as lead, thallium, and indium, which produce marked crystalline structure in gold, are, amongst metals, almost colloidal when pure. In these cases, then, the influence exerted by the added impurity can hardly be considered to be only due to a power to develop crystalline form. The question now arises, does this power to produce fragility correspond with any other property of metals in accordance with which they may be classified?

The facts represented in the Periodic Law were, in 1879, graphically represented by Lothar Meyer in his well-known curve of the elements. By adopting atomic weights as abscissæ and atomic volumes as ordinates, he showed that the elements can be arranged in a curve resembling a series of loops, the highest points of which are occupied by cæsium, rubidium, potassium, sodium, and lithium, while the metals which are most useful for industrial purposes occupy the lower portions of the several loops.

An examination of the results obtained in my experiments, so far as they have yet been carried, shows that not a single metal or metalloid which occupies a position at the base of either of the loops of Lothar Meyer's curve diminishes the tenacity of gold. On the other hand, the fact is clearly brought out that metals which do render the gold fragile all occupy high positions in Meyer's curve. This would appear to show that there is some relation between the influence exerted by the metallic impurities and either their atomic weights or their atomic volumes. It seems hardly probable that it is due to atomic weight, because copper, with an atomic weight of 63·2, has nearly the same influence on the tenacity of pure gold as rhodium, with an atomic weight of 104, or as aluminium, the atomic weight of which is 27. The atomic volume is, of course, obtained by dividing the atomic weight by the specific gravity of the element, and it at once becomes evident, from the tabulated results and from the diagrams which graphically represent them, that the metals which diminish the tenacity and extensibility of gold have high atomic volumes, while those which increase these properties have either the same atomic volume as gold or a lower one. Further, silver has the same atomic volume as gold, 10·2, and its presence in small quantity has very little influence, one way or the other, on the tenacity or extensibility

of the metal. When the metals are ranged in order of atomic volumes, potassium, which renders gold very brittle, assumes the position to which its very high atomic volume of 45 entitles it. Aluminium, indium, and lithium occupy somewhat abnormal positions on the diagram, for they possess high atomic volumes and yet they appear to increase the tenacity of gold, although they reduce its capability of being elongated.

The influence of cadmium in increasing the extensibility is very remarkable. Arsenic, again, has a higher atomic volume than gold, and should, therefore, render gold somewhat fragile. Several experiments were made with it, and the bars proved to be very fragile, but the results are not embodied in the table, as the bars did not appear to be uniform in composition. The influence of zirconium is also noteworthy. A fine specimen of crystalline zirconium was obtained from Messrs. Hopkin and Williams, but the metal appears to unite itself with gold with great difficulty. When wrapped in the foil and added to gold, purposely kept considerably above its melting point, the foil melted and released the zirconium, most of which fell, through the molten metal, to the bottom of the crucible, and remained there when the gold was poured out. After several attempts, an amount of material, which subsequently proved, on assay, to be about 0·2 per cent., was alloyed with the gold, and a perfectly sound bar obtained, which appeared to have extraordinary strength, for it broke with a load of 12 tons per square inch, pure gold breaking at 7 tons. Its fracture was remarkably close-grained, and it elongated 12 per cent. before breaking. If subsequent experiments should confirm this high tenacity, the result would be opposed to the view set forth in this paper, as zirconium has a high atomic volume, and should diminish the tenacity of gold.

It may be added that it was useless to employ anything but chemically pure gold, and the supply available only amounted to 40 ozs. As the preparation of gold of high purity occupies a considerable amount of time, it was considered best to publish the results already obtained. The effects of 0·2 per cent. of nickel, cobalt, iron, and platinum, which occupy very low positions on Meyer's curve, have severally been tried with *standard* gold, and do not appear to reduce either its tenacity or extensibility, and there is no reason to assume that they will behave differently in the case of *pure* gold.

Allusion has already been made to the close connection which exists between the tenacity of metals and their melting points, and Carnelley has pointed out that the melting points are inversely as the atomic volumes, "the only important exceptions to the rule being arsenic, selenium, tin, antimony, tellurium, thallium, lead, and bismuth." It can hardly be a matter of chance that, as my experiments prove, all these elements (with the exception of selenium, about the effect of which I am at present uncertain) diminish the coherence of gold, and there are but few others that do so—a fact which is alone sufficient to point to there being some connection between the action of minute quantities of impurities and the Periodic Law.

It would be difficult to suggest any explanation as to the mode of action of the various elements until the influence of each element in small but varying quantities, both singly and in association, has been investigated. Questions of much industrial interest present themselves, especially in connection with iron; with regard to this metal, the evidence as to the action of other elements

upon it would appear to tend in the same direction as in the case of gold, although the question is greatly complicated by the relations of iron to oxygen, and by the presence of occluded gases. It may be sufficient for the present to point out that the atomic volume of iron is 7·2; carbon, the atomic volume of which is small (4·0), when present in quantities varying from 0·2 to 1 per cent. increases its tenacity. Silicon, notwithstanding that it has a larger atomic volume (11·1) than iron, apparently increases its tenacity, although little can as yet be said as to its influence in very small quantities. The same observation applies to small quantities of manganese. This metal has an atomic volume of 6·8, and when present in very large quantities, 12 to 15 per cent., confers great extensibility on iron. Sulphur and phosphorus, on the other hand, have large atomic volumes, 15·1 and 13·2 respectively, and both these elements have, as is well known, a prejudicial effect on the qualities of iron.

It should not be forgotten that the knowledge of the effect produced on metals by small quantities of added matter has had a remarkable effect on the development of chemistry, mainly by sustaining the belief of the early chemists in the possibility of "ennobling" base metals or "degrading" precious ones. This is specially evident from the writings of Geber, Biringuccio, Gellert, and Robert Boyle; and it is hardly strange that, in the absence of a knowledge of analysis, they should have believed in the efficacy of a transmuting agent, when it is remembered that in the specimens submitted to the Society the presence of $\frac{1}{500}$ part of such metals as lead, bismuth, and potassium has entirely altered the appearance of the fractured surfaces of pure gold.

Addendum.

The test pieces were all cast in the same mould, and their sectional area was about 0·06 of a square inch; the sixth column of the table gives the reduction per cent. in sectional area of many of the test pieces at the point of fracture, so far as it was possible to measure them, but the irregular nature of the fractured surface rendered the measurements for the most part untrustworthy, and it would, therefore, be of but little use to plot these data on a curve. The behaviour of several of the test pieces under longitudinal stress resembled that of a viscous solid, and in such pieces the fracture was wedge-shaped, with a more or less sharp edge, the section remaining rectangular.

In some cases, notably in that of the test pieces containing palladium and lithium, the fractures revealed the presence of a minute cavity, which, doubtless, determined the point of fracture, and to some extent, therefore, affected the tenacity. With reference to this point, it is worthy of remark that Prof. Bauschinger, of Munich, has demonstrated, by the aid of a remarkable series of test pieces of iron and steel exhibited at the Nuremberg Exhibition of 1882, that the presence of a minute defect at the point at which fracture ultimately takes place, while not greatly affecting the tensile strength of the test piece, may, nevertheless, prevent the metal from contracting to so small an area as would have been the case if the metal had been perfectly sound. The elongation of the test pieces (given in the third column of the table) and the atomic volume of the added impurity are plotted in diagram No. II., Plate XVIII., which agrees closely with diagram No. I., representing

tensile strength and atomic volume. Cadmium exhibits marked irregularity in both diagrams, but the only striking difference between the two diagrams is presented by tellurium and bismuth, the former of which seems to be more prejudicial to the elongation of gold than to its tenacity. It may be added that some of the metals, zinc and rhodium for instance, although possessing smaller atomic volumes than gold, appear to diminish its elongation while they increase the tenacity of the precious metal. The diminution, though not very marked, causes an irregularity in the portion of the diagram occupied by metals with smaller atomic volumes than gold.

Mode of Purifying the Gold employed in the Experiments.

The gold employed in the foregoing experiments was purified by a method which was adopted, after much careful consideration, by the author of this paper in the preparation of the "Trial Plate" of gold which, by the direction of the Lords Commissioners of H.M.'s Treasury, was to supplement the "Standard Trial Plate," the use of which, for verifying the composition of the coinage, has been prescribed by law since the seventeenth year of King Edward IV. The purity of the gold so prepared has been recognised by M. Stas, and Mr. Lockyer has also satisfied himself of its high degree of purity by a comparison of photographs of its spectrum. The gold, having been used in the Assay Office of the Mint throughout a long period of years, had already been purified many times, and the only metallic impurities liable to have become associated with it were silver, platinum, and lead; and those only in very minute quantities. This gold was dissolved in nitro-hydrochloric acid, the excess of acid being driven off by slow evaporation. Platinum and the allied metals were carefully sought for, but were not detected, and the chloride of gold was then dissolved in a large quantity of distilled water, so that each gallon contained about 1 oz. of metal. This solution was allowed to rest for three weeks, when the finely-divided chloride of silver was separated by careful decantation of the supernatant solution. The last traces of chloride of silver are only thrown out of solution when chloride of gold is rendered very dilute. A warm solution of oxalic acid was then added, to precipitate the gold; the first and last portions of the gold precipitated were rejected, the middle portion being carefully washed with hot hydrochloric acid of specific gravity 1·1, afterwards melted, with the addition of bisulphate of potash, in a clay crucible and cast in a stone mould.

There are other methods of obtaining pure gold, which are, in some respects, more simple, and the best of these is, perhaps, that which involves the precipitation of gold from its chloride by the passage of a stream of pure sulphurous anhydride. The author believes, however, that the method above described is the most trustworthy, a view which is confirmed by Messrs. Hofmann and Krüss, who, in a recent paper,[1] state the results of submitting to a careful examination certain methods employed for separating gold from other metals, and they conclude that oxalic acid is the best reagent for separating gold from platinum, which was the metal the presence of which the author was most anxious to avoid. In discussing the results obtained by Messrs. Hofmann and Krüss, Mr. W. Bettel [2] points out that for large quantities of gold sulphurous anhydride is not a suitable precipitant.

[1] *Liebig's Annalen*, vol. ccxxxviii., 1887, p. 66. [2] *Chemical News*, vol. lvi., 1887, p. 133.

ON CERTAIN PROPERTIES OF METALS CONSIDERED IN RELATION TO THE PERIODIC LAW.

[*From the "Proceedings of the Royal Society,"* 1891, vol. xlix., pp. 347-356.]

In a previous paper published in the *Philosophical Transactions* (1888, A, pp. 339-349), the effect of about 0·2 per cent. of impurities on the mechanical properties of gold was examined, the results of the experiments showing that metals which diminish their tenacity and extensibility have high atomic volumes, while those which increase these properties have either the same atomic volume as gold or a lower one. The behaviour of aluminium and of lithium appeared to be somewhat exceptional. Gold contaminated with 0·2 per cent. of aluminium should, if the theory set forth in the paper be correct, have a tensile strength of about 7 tons per square inch; but it was found to be capable of sustaining a load of nearly 9 tons per square inch without breaking. It became necessary, therefore, to ascertain whether the cooling of a mass of gold containing aluminium presents any peculiarities, more especially as Osmond's [1] recent work leads to the conclusion that a pure metal can exist in two distinct molecular forms, and that the passage of the ordinary modification of a metal to the allotropic one may either be hastened or retarded by the presence of impurity.

In order to continue the investigation, a trustworthy pyrometer was needed, and this has fortunately been provided by the thermo-electric junction of platinum, and platinum with 10 per cent. of rhodium, the use of which was suggested by M. le Chatelier.[2] It appears to be superior to any other of the thermo-junctions which have previously been used, and some experiments made in 1889 satisfied me that the appliance is an extremely delicate and useful one for temperatures between 500° and 1,100° C. In a recent report to the Institution of Mechanical Engineers, in which details of the method of calibration are embodied, I have described a suitable arrangement for obtaining, by the aid of photography, autographic curves which represent the cooling or heating of masses of metal.

It consists in enclosing a galvanometer of the Déprez and d'Arsonval type in a large camera; a fixed mirror being placed below the movable mirror of the galvanometer, so that the light, from a lime cylinder reflected in a third mirror, passes to both galvanometer mirrors, and is reflected in the direction of a fine horizontal slit, behind which a sensitised photographic plate is drawn vertically, past the slit, by means of gearing driven by clockwork. The ray from the fixed mirror is interrupted periodically by a vane, and a beaded datum line is given which enables any irregularity in the advance of the plate to be detected.

The amount of divergence from its datum line of the spot of light reflected by the movable mirror at any given moment bears a relation (which can

[1] *Comptes Rendus*, vol. cx., 1890, p. 346. *Journ. Iron and Steel Inst.*, 1890, part I., p. 38.

[2] *Bull. Soc. Chim.*, Paris, vol. xlvii., 1887, p. 2. *Journal de Physique*, vol. vi., 1887, p. 23.

readily be found by calibration) to the temperature to which the thermo-junction is heated, and variations of temperature are recorded by a curve, which is the resultant of the upward movement of the plate and the horizontal movement of the spot of light. [The complete arrangement was shown in a diagram. The portion of the arrangement in which the thermo-junction is placed was also shown, drawn on a larger scale.]

The thermo-junction is inserted in a tubulure of a specially constructed crucible of plumbago, which contains about 5 ozs. of pure molten gold, and is allowed to cool down slowly inside a vessel of silver, 105 mm. diameter, and polished internally. The cylinder is of tin plate, polished internally and blackened outside.

[A photographic record of the cooling of pure gold was represented by a diagram.] The mass of gold had in this case an initial temperature of about 1,250° C., which fell to 1,045° C. when the mass began to solidify. The curve is approximately horizontal during solidification, and throughout its entire course appears to be a perfectly normal curve of a cooling mass of metal, no points of exceptional absorption or evolution of heat, such as would occur in iron, being observable.

[A curve obtained in a similar way, and representing the cooling of gold with 0·5 per cent. of lead, was shown by a thin dotted line in the same figure.] It is similar to the one representing the cooling of pure gold, but it will be evident that the presence of lead lowers the freezing point of gold by an amount which is found by measurement to be about 7·5° C.

A very different molecular condition is, however, established by the presence of aluminium. With 0·47 per cent. of this element the true freezing point can be detected, but is nearly obliterated, and the mass does not become truly solid until the point is reached when the temperature has fallen to 900° C.

It is of interest to ascertain how far the lowering of the freezing point of gold is in accordance with the results of Raoult's investigations on the lowering of the freezing point of solutions. His generalisations have been tested in the case of solutions of metals in metals with low melting points (tin, lead, and bismuth), in an admirable series of experiments by Heycock and Neville.[1] In order to calculate the lowering of the freezing point of gold produced by one atom of the added element to 100 atoms of the solvent, which has been the usual method of stating such results, it is necessary to know the latent heat of fusion of gold, and this had not been determined, probably because the accurate measurement of the latent and specific heats of metals with high melting points, such as gold, presents many more difficulties than the determinations of similar constants for bodies having low melting points.

Violle[2] found the specific heat of platinum at different temperatures by heating a piece of the metal in a specially constructed muffle, the temperature being simultaneously determined by means of a porcelain air-thermometer. The temperature of the metal being known, he plunged it into a calorimeter, and calculated from the data he obtained the mean specific heat of platinum between the extreme temperatures of the experiment. By making many experiments at different temperatures, he was able to deduce the specific

[1] *Journ. Chem. Soc.*, vol. lv., 1889, p. 666; vol. lvii., 1890, pp. 376 and 656.
[2] *Comptes Rendus*, vol. lxxxv., 1877, pp. 543-546.

heat of platinum at any point within the range, and he found that it regularly increased with the temperature. The data, thus afforded, enabled him to obtain the freezing point of platinum by transferring metal just *after* solidification into the calorimeter. Further, by pouring metal just *before* its solidification into water, it was easy to determine the total amount of heat evolved during cooling. Hence, knowing the amount of heat evolved by the mass after it had become solid, and deducting this amount from the total heat transferred to the water by the melted platinum, he obtained the latent heat of fusion of the metal.

He also determined [1] the specific heat and melting point (1,045° C.) in the case of gold, but he does not appear to have ascertained what is the latent heat of fusion of the precious metal. The following experiments were therefore made, in order to afford a basis for calculating the theoretical lowering of the freezing point of gold which a given addition of impurity should produce.

A calorimeter of polished silver, 10·5 cm. diameter, and 15·5 cm. high, was supported upon three points of cork within a bright metallic vessel, blackened externally, and constituting an air jacket. The amount of water employed varied from 800 to 1,088 grammes. The stirrer was a thin sheet of mica, mounted upon a silver wire, bent at its lower end into the form of a hoop; the mica also served to catch the gold poured into the water. In experiments E to I, the stirring was effected by silver vanes, of a form suggested by Prof. Rücker, actuated by a small electro-motor. Quantities of very pure gold, varying from 68 to 123 grammes, were melted in a small clay crucible and poured into the calorimeter.

This portion of the manipulation was performed by my assistant, Mr. Groves, whose long experience in melting gold enabled him to select the latest moment before solidification at which the gold could be poured. In experiments A and B and E to I, the temperature of the molten mass was measured, by the aid of the thermo-junction previously described, which was placed directly in the molten gold, up to the moment of pouring, and it is believed that the temperature of the mass was known to within 10° C.

At the end of each experiment, the gold poured into the calorimeter was carefully collected and weighed. The thermometer used was a very sensitive one with fixed zero, and made by Hicks, of Hatton Garden; it could easily be read to 0·02° C. The depth of water employed was sufficient to prevent the evolution of steam, and none was observed to escape in any of the experiments recorded.

The calculations are as follows:—

Let P = weight of water in calorimeter.
p_1c_1 = water equivalent of calorimeter.
p_2c_2 = ,, ,, thermometer.
p = weight of gold employed.
c = average specific heat of gold (Violle).
t = initial temperature of the molten gold.
T = ,, ,, water.
t_1 = final temperature of the water.

[1] *Comptes Rendus*, vol. lxxxix., 1879, pp. 702, 703; xcii., 1881, pp. 886-888.

The total quantity of heat carried to the calorimeter by p grammes of gold consists of the amount of heat which was required to raise the temperature of the metal to its melting point, *plus* the amount actually required to melt it; or

$$(P + p_1c_1 + p_2c_2)(t_1 - T) = pc(t - t_1) + p\lambda,$$

where λ is the latent heat of fusion of gold required;

$$\therefore \lambda = \frac{(P + p_1c_1 + p_2c_2)(t_1 - T) - pc(t - t_1)}{p}.$$

Taking, therefore, 16·3 as the latent heat of fusion of gold, and proceeding to find the lowering $\delta\theta$ of the freezing point, due to the presence of an impurity,

$$\delta\theta = \frac{\theta\omega}{\lambda\rho},$$

where θ = freezing point of gold, from absolute zero,
ω = osmotic pressure in dynes,
ρ = density of the solvent,
λ = latent heat of fusion of the solvent in dynes.

Inserting values

$$\delta\theta = \frac{\dfrac{1040 + 273}{1} \times \dfrac{(1013 \times 10^3 \times 22{\cdot}3 \times 1300)}{19{\cdot}6 \times 273}\rho}{\rho \times 16{\cdot}3 \times 41{\cdot}6 \times 10^6}$$

$$= \frac{1313 \times 1013 \times 22{\cdot}3 \times 1300}{19{\cdot}6 \times 16{\cdot}3 \times 41{\cdot}6 \times 10^3 \times 273}$$

$$= 10{\cdot}6^\circ \text{ C.}$$

Experiments are in progress with a view to ascertain whether the mean specific heat of very pure gold is the same as that found by Violle, for there is every reason to believe that the presence of impurity has great influence upon this constant. A few measurements already made would seem to indicate that his result is low, and this is important, because a slight difference in the specific heat will have a material effect upon the latent heat of fusion, and consequently on the theoretical atomic fall in the freezing point produced by aluminium. In order to ascertain whether aluminium would give the normal lowering of the freezing point (10·6° for each atom present in 100 atoms of gold) a crucible, fitted with a tubulure, as already described, was taken, and 130 grammes of very pure gold was melted in it. The crucible was then placed over the thermo-junction, and allowed to cool, the freezing point of the metal it contained being recorded in the usual way by a curve. The gold was then re-melted, and a weighed quantity of aluminium added, the mass being stirred and the temperature of its freezing point measured and recorded in a curve.

The addition of 0·2 per cent. of aluminium produced an appreciable fall in the freezing point, but this initial fall is only indicated by a change in direction of the curve. The fall as measured upon the photographic plate is only 1 mm., which, nevertheless, corresponds to a difference of temperature of 7·68° C.

TABLE OF EXPERIMENTS. IN CENTIGRADE-GRAMME UNITS.

	P.	p_1c_1.	p_2c_2.	p.	c.	t.	T.	t_1.	λ.	Remarks.
A, . .	800·75	15·42	0·86	84·72	0·0352 Violle	1,075° *	13·4°	19·0°	16·83	
B, . .	800·75	15·42	0·86	68·68		1,050° *	12·9°	17·4°	17·07	
C, . .	933·1	15·72	1·16	87·11		1,045° *	9·68°	14·52°	16·51	Solidification had just begun.
D, . .	808·7	15·72	1·16	76·05		1,045°	10·34°	15·18°	16·29	
E, . .	1088·6	16·37	1·16	119·6		1,045° *	11·79°	17·47°	16·36	
F, . .	1088·6	16·37	1·16	123·0		1,045° *	11·74°	17·50°	15·62	
G, . .	1088·6	16·37	1·16	79·19		1,045° *	12·11°	15·88°	16·43	
H, . .	1088·6	16·37	1·16	105·05		1,085° *	13·52°	18·61°	16·05	
I, . .	1088·6	16·37	1·16	102·75		1,070° *	14·30°	19·21°	15·87	**16·33.** Mean of the nine experiments.

* These temperatures were measured by the aid of the pyrometer, and, as the metal was slightly above its melting point, it was necessary to assume that the specific heat of the fluid gold is practically the same as that of solid gold near its melting point. The slope of the autographic curves, moreover, shows that any error so introduced would be but small. (*April* 20, 1891.—Experiments E to I have been added since the paper was read.)

A further addition of 0·2 per cent. of aluminium (making 0·4 per cent.) increased the fall to 1·8 mm., corresponding to 14·28° C. It may be urged that these measurements are small, but the observations were repeated with a scale some distance from the galvanometer, and chronographic records gave results having the same values.

An experiment with gold in which 1 per cent. of aluminium was present also confirms this; the fall in temperature of the freezing point was in this case 33·66° C., but there were indications that the gold, the solvent, was becoming saturated.

Now 0·2 per cent. of aluminium corresponds to $2/10 \times 196/27{\cdot}5 = 1{\cdot}42$ atom per 100 atoms of gold.[1]

Hence the fall per atom present per hundred atoms of gold $= 7{\cdot}68/1{\cdot}42 = 5{\cdot}4°$ C.

Similarly, a percentage of 0·4 corresponds to $4/10 \times 196/27{\cdot}5 = 2{\cdot}85$ atoms per hundred of gold, and the fall per atom $= 14{\cdot}28/2{\cdot}85 = 5{\cdot}0°$ C.

With 1 per cent. of aluminium the total fall will be due to 7·16 atoms per hundred of gold; hence the atomic fall will be $33{\cdot}66/7{\cdot}16 = 4{\cdot}7°$ C.

It may be added that experiments (as yet incomplete) seem to show that lead, bismuth, silicon, and platinum cause a much greater "atomic fall" in the freezing point of gold than aluminium does.

The relations of aluminium to gold would, therefore, appear to be peculiar in more ways than one. The curve clearly indicates that aluminium has a remarkable influence on the cooling of a mass of gold, and in view of this it would seem strange that calculations based on the atomic weight of aluminium should show that it delays the *initial* solidification of gold less than other elements. The *complete* solidification is, however, much retarded; for merely stirring a mass of gold contaminated with very little aluminium reveals the fact that the added element has set up during the solidification of the mass a "pasty stage," which continues through an unusually long range of temperature.

In the metallurgy of iron, aluminium is known to play an important part, and the introduction of a small quantity of it renders it possible to cast very mild steel or even "wrought" iron into forms which are remarkable for delicacy and soundness. The mode of action of the aluminium on iron in the "mitis castings" has given rise to wide divergence of opinion, but the view that it acts by the removal of oxide, or of occluded oxygen, has gained much favour. In the case of gold, which has neither occluded oxygen nor oxide to lose, the castings of the metal with 0·2 per cent. of aluminium are also remarkably sound, and, as experiments prove, very tenacious; the action of the aluminium is, therefore, probably a molecular one of much complexity.

It may be pointed out that the presence in gold of quantities of silver which vary from 0·1 to 4·0 per cent. does not lower the freezing point of the mass. Messrs. Heycock and Neville, who witnessed certain of the experiments above described, inform me of the hitherto unpublished fact, observed by them, that the presence of thallium does not lower the freezing point of lead.

The close concordance in both these cases between the atomic volumes

[1] 196 is the atomic weight of gold, 27·5 that of aluminium.

of the mass of metal and the added impurity is of special interest in connection with the generalisation given in my earlier paper, and re-stated on the first page of this. Silver has the same atomic volume as gold, and if present in small quantity produces no effect either on its tenacity or its freezing point.

Throughout these experiments gold has simply been employed for the sake of its freedom from liability to oxidation, but other metals must be studied, and it is worthy of record that Hadfield has recently shown that the parts played by aluminium and by silicon in steel are almost identical. Most of the physical properties of aluminium and silicon, in a free state, are totally different, but they possess the same atomic volume, and when they are alloyed with iron they affect it in precisely the same way.

I have to express my thanks to my assistant, Mr. H. C. Jenkins, for his aid in conducting these experiments.

[*April* 20, 1891.—In the course of the investigation, it became evident that, as is the case when aluminium is alloyed with copper or iron, the addition of aluminium to gold is attended with evolution of heat. The following experiment was, therefore, arranged, with a view to obtain evidence on this point :—

A mass of 30 grammes of gold, contained in an unglazed porcelain crucible, was placed in the centre of a block of firebrick and strongly heated up to well above the melting point of the metal. The thermo-junction was inserted directly in the gold, and the spot of light from the galvanometer allowed to fall in the usual way on to the sensitised plate. A piece of cold aluminium, equal in weight to 1 per cent. of the mass of gold, was then added and rapidly stirred. The autographic curve showed that the first effect of the added aluminium is, as might be expected, to lower the temperature of the gold to a point which proved to be close to its solidifying point, 1,045° ; the temperature instantly rises, however, to a point which is 225° higher than the initial temperature of the gold. The experiment is not strictly quantitative, as the perfect admixture of the aluminium could not be ensured ; but it is probable that true combination of aluminium and gold has taken place, which would doubtless greatly affect the physical constants of the mass.]

ON THE DIFFUSION OF METALS.

BAKERIAN LECTURE TO THE ROYAL SOCIETY, 1896. *Phil. Trans. A.*, vol. clxxxvii., pp. 383-415.

Part I.—Diffusion of Molten Metals.

GOLD, PLATINUM, AND RHODIUM, DIFFUSING IN MOLTEN LEAD AND IN MOLTEN BISMUTH.

The diffusion of molten and solid metals has long demanded investigation, their molecular mobility being of great interest in relation to the constitution of matter, and its results of much industrial importance.

The analogy of alloys to ordinary saline solutions has often been pointed out, and many experiments have recently been devoted to comparing the action of osmotic pressure in saline solutions and in alloys, as measured by the lowering of the freezing point, which is caused by the addition to the solvent of a small quantity of another body.[1] The general effect is the same whether the solvent is a liquid like water or a molten metal. Very little attention has, however, been given to the consideration of the molecular movements which enable two or more molten metals to mix spontaneously and form a truly homogeneous fluid mass, although it is by such an investigation that the analogy of an alloy to a saline solution may reasonably be expected to be more clearly revealed than by any other method of research. A single example of the spontaneous mixing of two metals may be useful. In preparing the alloy of gold and copper used for coinage, some 33 kilos. of gold and 3 kilos. of copper are melted together in a single crucible, and the results of assays on the first and the last portions of metal poured from the crucible, seldom differ by more than one ten-thousandth part. Such a fluid mass of standard gold owes this remarkable uniformity in composition not only to the mechanical stirring by which the blending of the gold and copper was roughly effected. The molecular mobility of the metals has influenced the result, and the metals dissolved in each other, become, by a spontaneous process, spread or diffused uniformly; in this case the uniformity is not materially disturbed when the solidification of the mass is effected.

In view of the great interest connected with such action, the absence of direct experiments is remarkable, but this may perhaps be explained by the difficulty of conducting them. The sources of these difficulties are many. Such metals as are suitable for study require a more or less elevated temperature to melt them, and, where diffusion is concerned, small variations in temperature may be of much importance, for, as Graham showed, the rate of diffusion of salts in water is greatly increased by a small rise in temperature, the diffusibility of chloride of sodium, for instance, being more than doubled by a rise of 33°. It is now well known that the osmotic pressure of a salt

[1] Heycock and Neville, *Trans. Chem. Soc.*, vol. lv., 1889, p. 666; vol. lvii., 1890, pp. 376 and 656; vol. lix., 1891, p. 936; vol. lxi., 1892, pp. 914 and 888; vol. lxv., 1894, pp. 31 and 65; vol. lxvii., 1895, p. 1024; and Roberts-Austen, *Proc. Roy. Soc.*, vol. xlix., 1891, p. 347.

in solution is measured by the diffusion which takes place. A rise of temperature, therefore, which augments the osmotic pressure, must also increase the rate of diffusion. Graham further pointed out that the inequality of diffusion which various saline substances exhibit at a low temperature, becomes less at a high temperature, and he, therefore, concluded that "it would appear to be the effect of a high temperature to assimilate diffusibilities" of different salts.[1]

In the case of molten metals, the necessity for working at high temperatures, which until quite recently could not be readily measured even with approximate accuracy, and the fear that the value of the results would be impaired by the action of convection currents, must have deterred physicists from undertaking experiments on the diffusion of molten metals. Ostwald's statement [2] with reference to the diffusion of salts, that "to make accurate experiments on diffusion is one of the most difficult problems in practical physics," may well have given rise to doubts whether any method which seemed to be available for conducting such investigations with molten metals would afford trustworthy results. The difficulties are obvious, but my long connection with Graham's researches made it almost a duty to attempt to extend his work on liquid diffusion to metals, and, therefore, fourteen years ago the present investigation was undertaken, but it was abandoned because I was unable to measure with sufficient accuracy the temperature at which diffusion took place, and it has only been resumed during the past two years.

As regards the history of the subject, I believe that a brief communication of my own on the mobility of gold and silver in molten lead, to the Chemical Section of the British Association at the meeting at Southport in September, 1883, embodied the results of the first experiments which have been made with the direct object of investigating the diffusion of molten metals and alloys, other than those of mercury which are fluid at the ordinary temperature. I stated that "while molten copper and antimony interpenetrate but slowly, the mobility of gold and silver in molten lead is comparatively rapid." [3] As regards mercury and its fluid amalgams, the history is more extended, for in 1713 Homberg [4] may be said to have at least foreshadowed the diffusion of metals, both solid and liquid, in his paper "On Substances which penetrate and which pass through Metals without their being Melted." He incidentally showed, by experiment, the extreme rapidity with which mercury will penetrate a bar of tin.

In November, 1883, Guthrie [5] published a remarkable paper "On Certain Molecular Constants," in which the diffusion of zinc, lead, tin, sodium, and potassium in mercury was studied, and he stated that these metals, which, of course, are much lighter than mercury, "appear after a month's interval in appreciable quantity at a depth of a foot beneath the surface, when the temperature is about 16° or 17°." He concludes his paper by offering "a general curve of amalgamation," which he thought would represent the

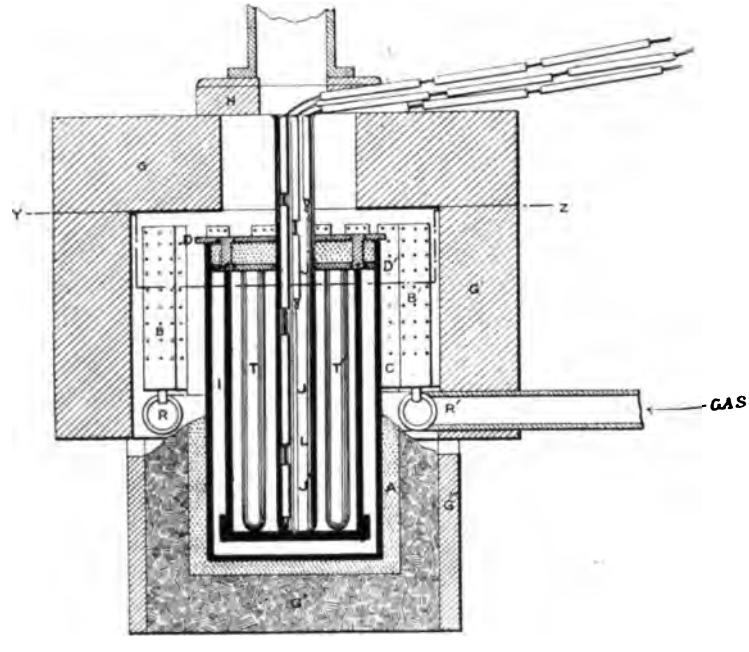
[1] Graham, "Collected Papers," p. 570, or *Phil. Trans. Roy. Soc.*, 1861, pp. 183-224.
[2] Ostwald, "Solutions," English Edition, 1891, p. 122.
[3] Roberts-Austen, *British Association Report*, 1883, p. 402.
[4] Homberg, *Mém. de l'Acad. Royale des Sciences*, 1713 (vol. published 1739), p. 306.
[5] Guthrie, *Phil. Mag.*, vol. xvi., 1883, p. 321. W. S. Humphreys has recently made experiments on the diffusion of zinc, lead, tin, bismuth, silver, and copper in mercury. *Trans. Chem. Soc.*, vol. lxix., 1896, p. 243.

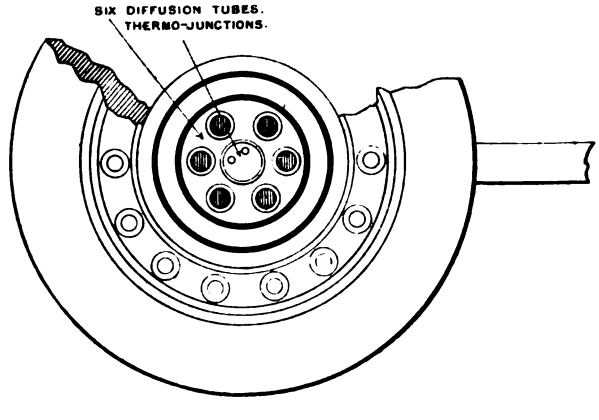
rate at which the metals examined by him alloy with mercury, and this curve may also, he says, "represent the relative rates of elementary atomic and molecular diffusion generally."

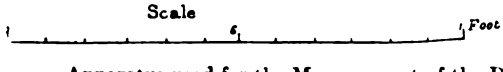
Guthrie held that as the mercury he employed was a good conductor of heat, there was not much fear of the disturbing influence of convection currents. The existence of such currents, nevertheless, gave me much anxiety in the earlier experiments with molten metals which were begun in the year 1881, and will now be described.

From the outset of this research both molten lead and bismuth were chosen as suitable fluids in which the diffusion of other metals could be studied. Advantage was also taken of the fact that at temperatures well above the melting point, neither of these metals unite with iron. The precious metals, also, when alloyed with lead or bismuth, do not show any tendency to unite with iron unless it is very clean and bright. Tubes of wrought iron, therefore, proved to be most useful in conducting the inquiry. In the first instance single tubes filled with lead were arranged vertically in a bath of lead which was kept well above its melting point. Weighed quantities of heated, but still solid, gold or platinum were then rapidly lowered through the lead in little covered receptacles of iron to the bottom of the tube, and when by the aid of a rigid steel wire the removal of the covers was gently effected, the gold was exposed to the lead; it became rapidly dissolved, and diffusion began. The tubes filled with molten lead, in which diffusion took place, were about 200 mm. long, and many such tubes were arranged in a single bath, which was carefully kept hotter at the top than at the bottom, so as to avoid as much as possible the carrying of the precious metal upwards by any streams of lead which might rise as convection currents from the bottom of the tube. The main result of these earlier experiments was to show that samples of lead (which were removed by sucking them from the upper part of the tubes into stems of tobacco pipes) always revealed the presence of weighable quantities of gold after a lapse of the first three hours, while a sample withdrawn at the end of a second period of three hours did not indicate the presence of a commensurate amount of the precious metal. This fact either pointed to defects in the method, to the transmission of gold by convection currents, or to the very rapid diffusion of gold when minute quantities of this metal are present in lead. I believe that the latter will ultimately prove to afford the true explanation of the facts observed.

The vertical tubes were then replaced by U-tubes of wrought iron, each limb of which was 230 mm. long and 10 mm. internal diameter. The tubes were filled with lead, and heated externally in a bath of molten lead, in an appliance which will be described immediately, and the precious metal, in the form of a rich alloy with lead, was inserted into one limb of the tube. Experiments proved that the gold falling by gravity became rapidly and uniformly distributed through the column of lead in that side of the tube, into which it was introduced, and in the rounded part of the tube, at the base of the U. After a given number of days the tubes were cautiously withdrawn from the bath and cooled from the bottom so as to solidify the alloy. The tube was then carefully divided by transverse saw cuts into measured sections, which were numbered consecutively, and the alloy could then be readily melted from each section and weighed, after which the amount of precious metal it contained was determined by analysis.







Apparatus used for the Measurement of the Diffusion of Metals.

It was found, however, that the use of U-tubes greatly increases the difficulties of calculation, as there is great uncertainty in any assumption as to the distribution of the diffusing metal during the experiment at points near the bend. It was found that in all these experiments the gold or platinum was very evenly distributed by gravity through the limb into which the metal was first introduced.

The calculations were finally made on the assumption that the concentration at the bend was, throughout the experiment, equal to the mean of its initial and final concentration. I, nevertheless, determined to sacrifice a long series of results, as they are less trustworthy than those obtained later by the use of single tubes.

[The description of the apparatus and the tabulated results of the experiments have been omitted, and use has been made of the abstract which appeared in the *Proceedings*.]

The continuation of the research was mainly due to the interest Lord Kelvin had always taken in these experiments. The want of a ready method for the measurement of comparatively high temperatures, which led to the abandonment of the earlier work, was overcome by the adoption of the recording pyrometer, and the use of thermo-junctions in connection with this instrument rendered it possible to measure and record the temperature at which diffusion occurred. Thermo-junctions were placed in three or more positions in either a bath of fluid metal or an oven carefully kept hotter at the top than at the bottom. In the bath or oven, tubes filled with lead were placed, and in this lead, gold, or a rich alloy of gold, or of the metal under examination, was allowed to diffuse upwards against gravity. The amount of metal diffusing in a given time was ascertained by allowing the lead in the tubes to solidify; the solid metal was then cut into sections, and the amount of metal in the respective sections determined by analysis.

It may be well to offer here a few general considerations respecting the phenomena to be observed.

It is now held that liquid diffusion is the result of osmotic pressure.[1] A movement of the particles (molecules or atoms) of the dissolved substance takes place, and a molecular force drives them from the place where they are more closely packed, and, therefore, exert greater pressure, and impels them to positions in which they are more widely distributed. This movement continues until the concentration, and, therefore, the pressure of the diffusing metal, is constant throughout the liquid. Graham's method of studying liquid diffusion consisted in filling wide-mouth phials of glass with the solutions of salts, which were allowed to diffuse outwards into water contained in capacious cylinders. This method could not well be imitated in the present experiments, as the manipulation, and the calculation of the results obtained by such a method present great difficulty. Hence the adoption in the present research of vertical tubes, as has already been described. In the earliest experiments made by me, in 1883, the little spheres of precious metal obtained from each measured section of lead were arranged on a card scale at measured distances;[2] each of the little spheres, therefore, represented the amount of

[1] Nernst, *Zeitsch. für Physikal. Chemie*, vol. ii., 1888, p. 613.

[2] Specimens of these records were exhibited to Section B of the British Association, at the Montreal Meeting, 1884.

gold in the section of the tube from which it had been derived, and their general appearance, when arranged as has just been described, suggested that a trustworthy method had been secured. It appeared probable that the law of diffusion of salts, framed by Fick, would also apply to the diffusion of one metal in another. Fick's law states that "the quantity of salt, which diffuses through a given area, is proportional to the difference between the concentrations of two areas infinitely near each other."

Fourier's theory of thermal conduction was applied by Fick to the phenomena of material diffusion generally. The law of diffusion is thus stated by Lord Kelvin[1]:—The rate of augmentation of the "*quality*," per unit of time, is equal to the diffusivity multiplied into the rate of augmentation per unit of space of the rate of augmentation per unit of space of the "*quality*." In the case of diffusion of salts or metals, the "*quality*" is concentration of the matter diffused, or deviation of concentration from some mean or standard considered.

The movement in linear diffusion is expressed, in accordance with Fick's law, by the differential equation

$$\frac{dv}{dt} = k\frac{d^2v}{d^2x}.$$

In this equation x represents distance in the direction in which diffusion takes place, v is the degree of concentration of the diffusing metal, and t is the time; k is the diffusion constant—that is, the number which expresses the quantity of the metal in grammes diffusing through unit area (1 sq. cm.) in unit time (one day) when unit difference of concentration (in grammes per c.c.) is maintained between the two sides of a layer 1 cm. thick. The experiments have shown that metals diffuse in one another just as salts do in water, and the results were ultimately calculated by the aid of tables prepared by Stefan for the calculation of Graham's experiments on the diffusion of salts.

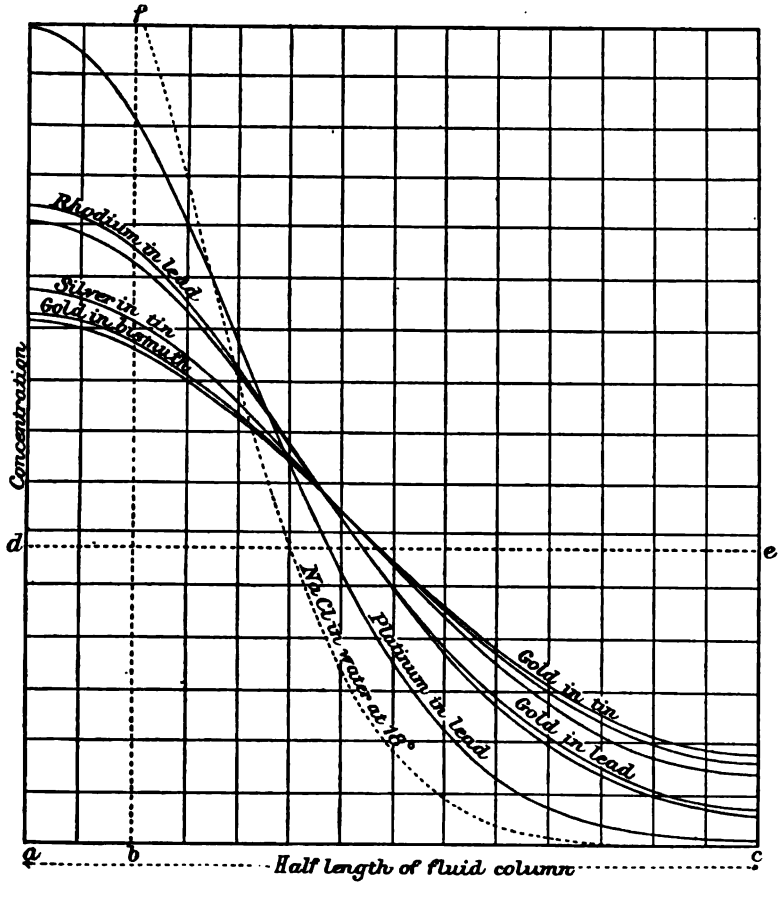
The necessary precautions to be observed and the corrections to be made are described at length, and the values of the diffusivity of various metals in lead are then given.

The values for k, the diffusivity, given in square cm. per day, are as follows:—

	k.
Gold in lead,	3·19 at 500°.
„ bismuth,	4·52 „
„ tin,	4·65 „
Silver in tin,	4·14 „
Lead in tin.	3·18 „
Rhodium in lead,	3·04 „
Platinum in lead,	1·69 at 490°.
Gold in lead,	3·03 „
Gold in mercury,	0·72 at 11°.

In order to afford a term of comparison, it may be stated that the diffusivity of chloride of sodium in water at 18° is 1·04.

[1] *Mathematical and Physical Papers*, vol. iii., 1890, p. 428.



Results of Diffusion for Seven days of Fluid Metals at 500° and of Chloride of Sodium in Water at 18°.

The author at present refrains from drawing any conclusion as to the evidence which the results afford respecting the molecular constitution of metals. It is, however, evident that they will be of value in this connection, because, with the exception of the gases, they present the simplest possible case of diffusion which can occur—the diffusion of one element into another.

Thus the relatively slow rate of diffusion of platinum as compared with gold points to its having a more complex molecule than the latter.

Part II.—Diffusion of Solid Metals.

Gold, Diffusing into Solid Lead.

The experiments described in the first part of this paper naturally suggested the enquiry whether gold would still permeate lead if the temperature were maintained at a point far below the melting point of lead. Would diffusion take place through solid lead at the ordinary temperature, or must a certain amount of viscosity be given to it by the application of a moderate heat? These were questions which demanded attention.

Historical.

The history of the diffusion of solids is full of interest, and it may be convenient, as far as possible, to group the facts which are known, rather than to deal with them in strict chronological order.

"*Kernel Roasting.*"—There has long been a prevalent belief that diffusion can take place in solids, and the practice in conducting certain important industrial processes supports this view. One of these processes, which is of comparatively ancient date, has certainly been employed since 1692 at Agordo, and its results are as follows:—When lumps of cupriferous iron pyrites are subjected to very gradual roasting with access of air, the copper becomes concentrated as a "kernel" of nearly pure sulphide of copper in the centre of a mass of ferric oxide, while, at the same time, the silver originally present in the ore travels outwards and forms a glistening shell on the exterior. These complicated changes must be effected in the solid by a movement allied to diffusion.

Cementation Processes.—Of all the processes which depend on the diffusion of solids probably the most interesting is the truly venerable one by which silver may be recovered from either plates or globules of solid gold by "cementation," the name being derived from the "cement" or compound in which the plates were heated. Its nature was indicated by Pliny, and the manipulation it involved was minutely described by Geber in the eighth century, as well as by many of the early metallurgists; Savot,[1] for instance, pointed out in the early part of the seventeenth century that "cementation" will deprive gold of the silver it contains, "however small" the amount of the latter metal may be, so that it will be evident that the elimination of the silver from the centre of a mass of solid gold must also be effected by an inter-molecular movement allied to diffusion. The evidence, however, is

[1] "Discours sur les Médailles antiques," 1627, p. 76.

not conclusive, because gaseous chlorine intervenes, and may even play an important part in the penetration of the solid metal.

In another ancient "cementation" process, the conversion of strongly heated but still solid iron into steel is effected by the passage of solid carbon into the interior of the mass of iron, and the explanations which have from time to time been given of the process form a voluminous literature. Le Play considered cementation, which is really a slow creeping action of one solid into another, to be "an unexplained and mysterious operation," and he attributed the transmission of the carbon to the centre of the iron solely to the action of gaseous carbonic oxide. Gay-Lussac [1] confessed that a study of the process shook his faith "in the belief generally attributed to the ancient chemists that *corpora non agunt nisi soluta*," for it is certain, he adds, "that all bodies, solid, liquid, or aëriform, act upon each other, but, of the three states of bodies, the solid state is the least favourable to the exercise of chemical affinity."

In 1881, M. A. Colson [2] communicated a paper to the Académie des Sciences, in which he showed that when iron is heated in carbon there is a mutual interpenetration of carbon and iron at so low a temperature as 250°. The interpenetration of solids, as distinguished from the diffusion of two metals in each other, has received attention from many experimenters, of whose work brief mention will only be given, as the subject of this part of the paper is the diffusion of solid metals. Colson pointed out that pure silver diffuses as chloride in dry chloride of sodium, and he states that calcium passes into platinum when the latter is heated in lime, and that silica diffuses through carbon and yields its silicon to platinum. The permeation of strongly heated porcelain by carbon has been demonstrated by Marsden, Violle, and other experimenters. Spring,[3] in 1885, showed that solid barium sulphate and sodium carbonate react on each other until an equilibrium is established.

Any lingering doubt as to whether gas need necessarily intervene in the cementation of iron was, I may point out, removed by an experiment of my own,[4] in 1889, which showed that pure iron may be carburised by diamond *in vacuo*, at a temperature far below the melting point of iron and under conditions which absolutely preclude the presence or influence of occluded gas. I am indebted to my friend, M. Osmond, for a photograph of a section, magnified 100 diameters, through a piece of electro-iron, which had been heated to 1,500° and carburised from the upper end by contact with the diamond form of carbon, and this section clearly shows the gradual penetration of the iron by carbon. The beautiful work of Osmond on the transformations of iron, and of iron and carbon, affords, moreover, a striking proof of the molecular mobility of solid iron at a temperature which is at least 600° below its melting point.

The history of the formation of alloys by cementation will be traced subsequently.

The Penetration of Solid Metals by Gases.—This subject was, as is well known, investigated by Graham, "the leading atomist of his generation," but before his attention was specially directed to it, a mass of experimental

[1] *Ann. de Chim. et de Phys.*, vol. xvii., 1846, p. 221.
[2] *Comptes Rendus*, vol. xciii., 1881, p. 1074; vol. xciv., 1882, p. 26.
[3] *Bull. de l'Acad. Roy. de Belgique*, vol. x., 1885, p. 204.
[4] *Nature*, vol. xli., 1889, p. 14.

evidence led him in 1863 to express views of singular interest in the beautiful paper [1] which embodied his "speculative ideas respecting the constitution of matter." In this paper he pointed out that in solids some of the molecules may still be in the liquid or even the gaseous condition, and his words are very definite. He says, "the three conditions (solid, liquid, and gaseous) probably always co-exist in every liquid or solid substance, but one predominates over the others. . . . Liquefaction or solidification may not, therefore, involve the suppression of either the atomic or the molecular movement, but only the restriction of its range." He subsequently, in 1866,[2] gave singular point to these speculations by his discovery of the penetration of solid metals by gases.

After Graham's death, evidence as to the molecular mobility of metals came slowly. E. Wiedemann [3] showed, in 1878, that solid metals were not necessarily inert, as changes which involve atomic movement take place in bismuth-lead alloys, and the clear evidence thus afforded of allotropic change in the solid, recently formed the subject of some experiments of my own.[4]

Confirmation of the accuracy of Graham's views as to the co-existence of liquid and gaseous molecules in a solid was afforded twenty years later by Prof. W. Spring.[5] In 1886 his admirable investigation on the solidification of alloys of lead and tin, afforded him experimental evidence that in these alloys active molecular movement is continued after the alloys have become solid. He says, and it is well to quote his interesting words, "on serait porté à penser qu'entre deux molécules de deux corps solides il y a un va-et-vient perpétuel d'atomes," and he adds, "if the two molecules are of the same kind, chemical equilibrium will not be disturbed, but if they are different this movement will be revealed by the formation of new substances."

Formation of Alloys by Cementation.—The fact that alloys can be formed by the union of two metals at a temperature below the melting point of the more fusible of the two has long been known to metallurgists, and perhaps the most striking fact in the more modern history of the subject was recorded in 1820 by Faraday and Stodart,[6] who, in the course of an investigation on alloys of iron with other metals, noted their failure to produce certain alloys by "cementation," but consider it "remarkable," in the case of platinum, that it will unite with steel at a temperature at which the steel itself is not affected. They also show that solid steel and platinum, in the form of bundles of wires, may be welded together "with the same facility as could be done with iron or steel," and they observe that on etching the surface of the welded mass by an acid "the iron appeared to be alloyed with the platinum." Their interest in this singular fact led them to promise some direct experiments on "this apparent alloy by cementation"—that is, by the interpenetration of solids. Since this time there have been many more or less isolated observations bearing on the subject, and brief reference may be made to the more

[1] *Phil. Mag.*, February, 1864; "Collected Papers," p. 299.
[2] *Phil. Trans. Roy. Soc.*, 1866, pp. 399-439.
[3] *Wied. Ann.*, iii., 1878, p. 237.
[4] "Second Report Alloys Research Committee." *Proc. Inst. Mech. Engineers*, 1893, p. 127.
[5] *Bull. de l'Acad. Royale de Belgique*, vol. xi., 1886, p. 355.
[6] *Quarterly Journal of Science*, vol. ix., 1820, p. 319.

important of them in chronological order. In 1877 Chernoff [1] showed that if two surfaces of iron of the same nature be placed in intimate contact and heated to about 650° they will unite. In 1882 Spring [2] made his remarkable experiments on the formation of alloys by strongly compressing their constituent metals at the ordinary temperature, while in 1885, O. Lehmann [3] suggested, and in 1888 Hallock [4] demonstrated that compression is not necessary, as alloys might be formed by placing carefully-cleaned pieces of two constituent metals in juxtaposition and heating them to the melting point of the alloy to be formed, which was, in some cases, 150° below the melting point of the more fusible of the two metals. In 1889 Coffin showed, and I have repeatedly verified the accuracy of his experiment, that if the freshly-fractured surfaces of a steel rod, 9·5 mm. square, be placed together and heated to below redness, they will unite so firmly that it is difficult to pull them apart by hand. The steel is highly carburised, and the diffusion of a carbide of iron probably plays an important part in effecting the union. There must have been molecular interpenetration in this case, though the steel was at least 1,000° below its melting point. In 1894 Spring [5] proved that if the carefully surfaced ends of cylinders of two metals were strongly pressed together and maintained for eight hours at temperatures which varied from 180° to 400°, interpenetration would take place, true alloys being formed at the junction of the two metals.

In these experiments, which are of great interest, the temperatures at which the cylinders were maintained were below the melting point of the more fusible of the two metals. Care appears to have been taken to avoid heating them up to the melting point of the *eutectic* alloy, though it was in some cases close to it. The necessity for this precaution will be obvious as the union of the two compressed cylinders might easily be effected by the fusion of an eutectic alloy with a relatively low melting point.

I observed in 1887 that an electro-deposit of iron on a clean copper plate will adhere so firmly to it that when they are severed by force a copper film is actually stripped from the copper plate and remains on the iron, thus affording clear evidence of the interpenetration of metals at the ordinary temperature. I found that this interpenetration of copper and iron will take place through films of electro-deposited nickel.[6] Mylius and Fromm have shown that metals interpenetrate and form alloys when they are precipitated by electrolysis from their aqueous solutions.[7]

The diffusion of metals in each other must be closely connected with the evaporation of solid metals or alloys at temperatures far below their melting points, and it will be well before describing the new experiments on diffusion in solid metals to briefly recall the facts which are already known. It is not necessary to go further back for definite views on the subject than to the time of Boyle,[8] who thought that "even such (bodies) as are solid may

[1] *Revue Universelle des Mines*, vol. i., 1877, p. 411.
[2] *Ber. der Deutsch. Chem. Gesell.*, xv., 1882, p. 595.
[3] *Wied. Ann.*, xxiv., 1885, p. 1.
[4] Communicated to Phil. Soc. of Washington, Feb. 18, 1888; *Zeitschr. Phys. Chem.*, vol. ii., 1888, p. 6, or *Chem. News*, vol. lxiii., 1891, p. 17.
[5] *Bull. de l'Acad. Royale de Belgique*, vol. xxviii., 1894, p. 23.
[6] *Journ. Iron and Steel Inst.*, No. 1, 1887, p. 73.
[7] *Ber. der D. Chem. Gesell.*, vol. xxvii., 1894, p. 630.
[8] "Collected Works." Shaw's edition, 1738, vol. i., p. 400.

respectively have their little atmospheres," . . . "for," he adds, "no man, I think, has yet tried whether glass, and even gold, may not in length of time lose their weight."

Boyle's opinion was correct, for mercury which has been *frozen* by extreme cold does, as Merget [1] showed two centuries later, evaporate into the atmosphere surrounding it; a fact which is of much interest in connection with Gay-Lussac's well-known observation that the vapours emitted by ice and by water both at 0° C. are of equal tension. Demarcay [2] has proved that *in vacuo* metals evaporate sensibly at lower temperatures than they do at the ordinary atmospheric pressure, and he suggests that even metals of the platinum group will be found to be volatile at comparatively low temperatures.

Thus he finds that cadmium volatilises at 160°, zinc at 184°, and lead and tin at 360°, and subsequently Spring [3] (1894) demonstrated that zinc is volatile at atmospheric pressure at about 300°, cadmium at about 400°, while even copper is slightly volatile at the latter temperature.

Moissan [4] has stated quite recently that the vapour tension of solid silicon enables it to unite with iron and chromium by true "cementation" at a temperature of 1,200°, which is much below the fusing point of these metals.

It must be borne in mind that the interesting facts recorded by the various experimenters whose names I have cited hardly come within the prevailing conditions in the ordinary diffusion of liquids, in which the diffusing substance is usually in the presence of a large excess of the solvent which is supposed to exert but little chemical action on it. This condition has been fully maintained in the experiments on the diffusion of liquid metals which are described in the first part of the present paper. It must also be remembered that Van't Hoff [5] has made it highly probable that the osmotic pressure of substances existing in a *solid* solution is analogous to that in liquid solutions and obeys the same laws, and it is also probable that the behaviour of a solid mixture, like that of a liquid mixture, would be greatly simplified if the solid solution were very dilute.

Nernst expresses the hope that it may be possible to measure by indirect methods the osmotic pressure of substances existing in solid solutions. I trust that the following experiments will sustain this hope by affording measurements of the results of osmotic pressure in masses of *solid metals* at the ordinary atmospheric pressure, and at a temperature at which it has hitherto been scarcely possible to detect diffusion in them.

The following experiments constitute, so far as I am aware, the first attempt to actually measure the diffusivity of one solid metal in another. It must be borne in mind that the union of two clean surfaces of metal, and even the interpenetration of two metals to a slight depth below the surfaces does not necessarily depend on diffusion alone, as the metals become united in a great measure by viscous flow. The nature of welding demands investigation, but the union of metals by welding is effected most energetically when the metals are in the colloidal condition, in which true diffusion is least marked. It may be observed that discs of gold and lead, pressed together at the ordinary

[1] *Ann. de Chim. et de Phys.*, vol. xxv., 1872, p. 121.
[2] *Comptes Rendus*, vol. xcv., 1882, p. 183.
[3] *Loc. cit.*, 1894, p. 42.
[4] *Comptes Rendus*, vol. cxxi., 1895, p. 621.
[5] *Zeitschr. Phys. Chem.*, vol. v., 1890, p. 322.

temperature for three months, were found to have welded together more perfectly than two similar discs kept in contact at 100° for six weeks, although at least ten times more metal had interdiffused in the latter case than in the former.

[The detailed description of the experiments and the tabulated results have been omitted, and use has been made of the abstract which appeared in the *Proceedings*.]

The author proceeds to describe his own experiments on the diffusion of solid metals. They are of the same nature as in the case of fluid metals, except that the gold, which is the metal chosen for examination, was placed at the bottom of a solid cylinder of lead instead of a fluid one.

In the first series of experiments, cylinders of lead, 70 mm. long, with either gold, or a rich alloy of gold and lead at their base, were maintained at a temperature of 251° (which is 75° below the melting point of lead) for thirty-one days. At the end of this period the solid lead was cut into sections, and the amount of gold which had diffused into each of them was determined in the usual way. Other experiments follow, in which the lead was maintained at 200°, and at various lower temperatures down to that of the laboratory. The following are the results :—

						k.
Diffusivity of gold in fluid lead at			550°,	.	.	3·19
,,	solid	,,	251°,	.	.	0·03
,,	,,	,,	200°,	.	.	0·007
,,	,,	,,	165°,	.	.	0·004
,,	,,	,,	100°,	.	.	0·00002

The experiments at the ordinary temperature are still in progress, but there is evidence that slow diffusion of gold in lead occurs at the ordinary temperature. The author points out that if clean surfaces of lead and gold are held together *in vacuo* at a temperature of only 40° for four days, they will unite firmly, and can only be separated by the application of a load equal to one-third of the breaking strain of lead itself.

The author thinks it will be considered remarkable that gold placed at the bottom of a cylinder of lead, 70 mm. long (which is to all appearance solid), will have diffused to the top in notable quantities at the end of three days. He points out that at 100° the diffusivity of gold in solid lead can readily be measured, though its diffusivity is only $\frac{1}{100,000}$ of that in fluid lead at a temperature of 500°. He also states that experiments which are still in progress show that the diffusivity of solid gold in solid silver, or copper, at 800° is of the same order as that of gold in solid lead at 100°.

[The following portions are continued from the *Transactions*.]

Welding of Gold and Lead, and Diffusion of Gold in Lead at the Ordinary Temperature.

The fact that two clean surfaces of lead will weld together at the ordinary temperature is well known. It may be well, however, to state in connection with the experiments of Demarcay (see p. 291) on the volatilisation of metals

in vacuo at comparatively low temperatures that if the ends of small bars of gold or silver be surfaced, pressed against lead, and maintained for four days *in vacuo* at a temperature of only 40°, the interpenetration of the two metals will be so complete that their separation can only be effected by the application of a load of 70 lbs. per square inch of the sectional area of the bars, or no less than $\frac{1}{3}$ of the breaking strain of lead.

It remains to be seen whether diffusion can be measured in solid lead at the ordinary temperature, and, with this object in view, cylinders have been prepared and set aside for future examination.

In searching for evidence of diffusion in solid metals at the ordinary temperature, it will be well to examine certain alloys used in art metal work by the Japanese, who often employ an alloy of copper containing a small proportion of gold (called *Shakudo*), which is soldered or welded in alternate layers with pure copper. The gold in the copper enables it to assume a beautiful purple patina when it is treated with suitable pickling solutions, which leave the pure copper of a red colour. In this way very singular banded effects are produced. Many of the specimens are centuries old, and I have attempted, by grinding away the existing patina and re-pickling the surface, to ascertain whether the widening of the coloured bands would show that, in the course of time, gold had diffused from the *Shakudo* layers and had passed into the copper. I believe that there is evidence that it does do so, but the enquiry is full of difficulty, and needs training in micrography, of which my friend, M. Osmond, is a master. We propose to study this part of the subject together, and I only allude to it here because, if diffusion occurs in copper, silver, and gold at the ordinary temperature, its results should be revealed in the products of this ancient oriental art.

Diffusion of Gold in Solid Silver.

A short cylinder of silver, containing 20 per cent. of gold, was pressed against the carefully-surfaced end of a cylinder of pure silver, 1 cm. in diameter and 2·5 cms. long. These cylinders were kept in an annealing furnace for ten days, at a temperature which never exceeded 800°, and was, therefore, 160° below the melting point of silver (960°). The lowest melting point of the gold-silver series of alloys is 850°. The cylinder was then cut into sections in the usual way, and the amount of diffused gold determined by analysis. As the temperature was intermittent the true diffusivity cannot be taken, but I am satisfied that the diffusivity of solid gold in solid silver at 800° is of the same order as that of gold in lead at 200°. It would appear, therefore, that the melting points of the metals have a dominating influence on the resistance offered to diffusion.

Diffusion from a Hot to a Cold Portion of Solid Metal.

It is well known that, in the liquid diffusion of salt solutions, osmotic pressure will drive molecules from the hot to the cold portions. Prof. Thorpe suggested that an experiment of this nature should be tried with solid alloys. The principle of "reflection," which would, of course, be involved in such an experiment, has already been alluded to under the liquid diffusion of metals (see Part I., p. 282). The difficulty is to obtain a solid alloy of uniform

composition, but, after many experiments, a rod of bismuth was obtained, in which it was believed that 3·75 per cent. of gold was uniformly distributed. This was arranged, as shown in Fig. 2, which represents, in sectional plan, a double block of brass, enabling half the rod to be heated to 170°, which is below the melting point of the bismuth-gold *eutectic* alloy, while the other half can be cooled by a stream of water. The heating was maintained for six days. The result proved that there was a distinct concentration of 0·1 per cent. gold at the point A, where the bar entered the cooled chamber. Similar results have been obtained with gold-lead alloys, and, if the bar be maintained at 240°, which is above the melting point of the *eutectic* alloy, the effect is very marked. I offer these statements with some reserve, as they require confirmation.

The data now published form but a small portion of the investigation which has been long in progress. The manipulation it involved was singularly difficult and tedious, and it would probably have been far less advanced than it is, if I had not had the advantage of the aid of one of my former students at the Royal School of Mines, Mr. Alfred Stansfield, B.Sc. He made the calculations which were necessary to extend Stefan's tables to the range

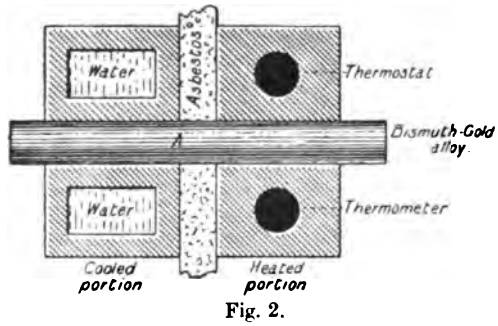


Fig. 2.

covered by the present experiments, and has shown untiring interest in conducting that part of the series which has been undertaken during the past two years.

The founder of this lectureship directed in 1768 that the subject be selected from "Such part of Natural History or Experimental Philosophy as the Council of the Royal Society shall be pleased to appoint," and in the century which followed the date of Mr. Baker's bequest, these branches of knowledge seemed to diverge widely. The investigation and measurement of molecular movement has, however, gradually joined them in the closer union which Graham did so much to effect. His work in experimental physics, more than that of any other investigator, taught the physiologist that tracing the relations of the phenomena of life as revealed in diffusion, transpiration, and osmosis will afford Natural History its most precious records.

The evidence gathered by the metallurgist of active atomic movement in fluid and solid metals may sustain the hope of the physiologist that he will ultimately be able to measure the atomic movements upon which vitality and thought depend.

ON THE DIFFUSION OF GOLD IN SOLID LEAD AT THE ORDINARY TEMPERATURE.

[*From the "Proceedings of the Royal Society,"* 1900, lxvii., pp. 101-105.]

In the Bakerian Lecture, "On the Diffusion of Metals," [1] delivered in 1896, evidence was given to show that gold placed at the base of a column of fluid lead 16 cm. high, maintained at a mean temperature of 492°, or 166° above the melting point of lead, diffuses to the top of the column in an appreciable amount in a single day, the diffusivity expressed in centimetre-day units being 3·0. If the lead be heated, say to 251°, or 75° below the melting point of the metal, diffusion takes place at a much slower rate: it may still be readily measured, though the diffusivity is only 0·023 in centimetre-day units. In the experiments on diffusion in solid lead, the latter metal was prepared with great care, and possessed a high degree of purity. The method of preparation consisted in the reduction of carefully purified carbonate of lead by cyanide of potassium, the reduced metal being cast in carbon moulds.

It became evident that at the ordinary temperature the rate of diffusion of solid gold in solid lead must be very slow, and I stated in the Bakerian Lecture that cylinders of lead had been set aside with discs of gold affixed to their bases, in order that, after a sufficient lapse of time, the diffusion occurring at the ordinary temperature might be measured. By the month of March in the present year, four years had elapsed since the experiment began, and the time appeared to be sufficiently long to justify the attempt to ascertain how far the gold had diffused. In starting the experiments the bases of the lead cylinders were carefully brought to a smooth surface, and the discs of pure gold were specially cleaned, the discs of gold being held against the bases of the cylinders by means of clamps. The laboratory in which the cylinders were placed consists of a vaulted chamber situated in the basement of the Mint, and its temperature varied but little from a mean of 18° C. The diameters of the cylinders were in all cases 0·88 cm., their lengths varied somewhat, the longest being 25 cm. At the end of the four years the discs of gold were found to be adherent to the lead. The cylinders were divided into thin slices at right angles to the axes of the cylinders, the first slice was approximately 0·75 mm. thick, but the succeeding layers were about 2·3 mm. thick. By the ordinary methods adopted by assayers, which were conducted with extraordinary precautions, gold was found in each of the four lower slices, while only the minutest traces of gold could be found in any slice beyond the fourth from the base. The amount of gold that had diffused in the different cylinders of lead was, however, not uniform. The variation is probably due to difference in contact between the cylinders of lead and the discs of gold. The results in all four experiments were, however, of the same order, and it will be sufficient to give the actual amounts of gold found in a single cylinder. The richest layer was, of course, the one in direct contact with the gold, and from it a globule of gold was extracted which weighed 0·00005 gramme. There is in the Mint a balance that will readily weigh such globules. The gold extracted from the second and third layers was too small to be weighed, but the amounts could be approximately determined by

[1] Delivered February 20, 1896. *Phil. Trans.*, A, vol. clxxxvii. (1896), pp. 383-415.

measurement under a microscope. [Actual photographs of the gold extracted from the successive layers of a cylinder were appended; the magnification being in all cases the same (56 diameters).]

It may be thought that the amounts are but small, but from the point of view of the assayer, who is accustomed to determine minute quantities of precious metal in large masses of material, the results assume very substantial proportions. Thus the amount of gold found in the richest layer of lead represents no less than 1 oz. 6 dwts. of gold per ton, which could be profitably extracted, while the amount in even the poorest layer is 1½ dwts. per ton.

The signification of these results may perhaps be made clearer if it is stated that the amount of gold which would diffuse in solid lead at the ordinary temperature in 1,000 years is almost the same as that which would diffuse in molten lead in a single day, provided no more gold is supplied in either case than can be held in solution. This will serve to show how important temperature is in relation to diffusion. As an example of the relative effects of temperature on this purely physical change and on a chemical change, it may be interesting to refer to the case of the dissociation of auric chloride. At the ordinary temperature, the tri-chloride of gold is very stable, though it decomposed rapidly at 180°, and my colleague, Dr. Rose,[1] has shown that, though the decomposition of auric chloride may be perceptible at a temperature of 70°, it would nevertheless require, at that temperature, about twenty-five years for its nearly complete change into monochloride.

I believe, with Robert Boyle, that though solid gold may have its "little atmosphere," "no man has yet tried whether gold may not in time lose its weight," but the rate at which gold can possibly evaporate into the air at the ordinary temperature must be far less than that at which it diffuses into lead. This shows that the action of a solvent for the gold is necessary, and this solvent is provided by bringing gold into contact with *solid* metallic lead.

I would express my warm acknowledgment to Dr. A. Stansfield, who aids me in conducting the Metallurgical Laboratory at the Royal College of Science, for the care he has devoted to the tedious manipulation involved in these experiments. His help has given me great confidence in the accuracy of the results. It may be well to add that I propose to prepare suitable cylinders of lead and gold on the lines indicated in this paper, and to offer them to the National Physical Laboratory with a view to their being examined after such a lapse of time as may be deemed fully adequate.

[*Note, May* 28.—In the Graham Lecture, delivered at Glasgow on the 18th of April last, after speaking of the diffusion of gold in solid lead, I stated that I was "trying to ascertain whether diffusion in the solid metal is, or is not, accelerated by the simultaneous passage of a strong electric current." I again referred to the subject in answer to Lord Kelvin during the discussion which followed the reading of the present paper, and stated that the experiments were incomplete. Such experiments take a long time, and it may be well to add that the arrangement was just as is described above, except that the lead ordinarily used for assaying was employed. Two cylinders, each 0·88 cm. in diameter, with gold clamped to their respective bases, were maintained at a temperature of 150° for 544 hours, beginning on the 31st of January

[1] *Journ. Chem. Soc.*, vol. lxvii. (1895), p. 904.

of the present year. A current of 1·5 amperes was passed through one of the cylinders only during the whole time, the current passing from the gold to the lead. The amount of gold which had diffused into each of the lead cylinders was then ascertained by the method which has already been described. Gold was detected at a height of 7·5 mm. in the case of the cylinder through which the current had passed, while in the other case with no current it had reached a height of 10 mm., the amount of gold in each section being also greater. Subsequent experiments showed that a part at least of this difference was due to imperfection in the contact between the lead and the gold. Other experiments are now in progress in which far greater current densities are employed.

If these experiments confirm the previous one, they will show that a solution of gold in lead does act, to a small extent, as an electrolyte. The following method was adopted for ensuring contact between the gold and the lead :—

My assistant, Mr. W. H. Merrett, succeeded in joining by fusion discs of gold between two cylinders of lead. Contact between the metals is, therefore, above reproach, but it will be many weeks before the results can be recorded.

Thirteen years ago I was unsuccessful in the attempt to electrolyse a solution of gold in metallic lead by the passage of a current of 300 amperes through the molten mass.[1] The failure may have been due to the fact that at the high temperature produced diffusion must have been very rapid. If, therefore, separation of gold from the lead did take place, uniformity of the solution may have been restored by diffusion. I succeeded in 1895 in obtaining some evidence as to the separation of gold from its solution in metallic lead by electrolysis through a glass septum.[2] This is, however, only indirectly connected with the electrolysis of alloys.]

[1] *British Association Report*, 1887, p. 341.

[2] "Third Report to the Alloys Research Committee." *Proc. Inst. Mech. Engineers*, 1895, p. 240.

ON THE STRUCTURE OF METALS, ITS ORIGIN AND CHANGES.

(In Collaboration with F. Osmond.)

[*From the "Transactions of the Royal Society,"* 1896, vol. clxxxvii., pp. 417-432.]

It has been shown by Herbert Tomlinson that the atomic volume of metals is intimately connected with their thermal capacity [1] and with Young's modulus.[2] He considers in view of the work of Wertheim,[3] of Maxwell,[4] and of Heen,[5] and as the result of his own experiments, that the value of the product of the elasticity E, when multiplied by a fractional power of the atomic volume, A/D, is a constant for all metals. $E\ (A/D)^{7/3} = 181 \times 10^4$. The divergencies shown by several metals from this mean value arise from the fact that the presence of small amounts of impurity makes a great difference in their elasticity.

Sutherland [6] finds a close relation between the atomic volume and the rigidity of metals, and considers that this rigidity is "in its essence a kinetic phenomenon almost as simple in character as the elasticity of perfect gases."

Prof. Fessenden,[7] moreover, has urged that the cohesion of metals is proportional to some power of the atomic volume, and he considers that the rigidity varies as the fifth power of the distance of the centre of the atoms, or as (atomic volume)$^{5/3}$. These facts are given merely to show that the atomic volume of the added element is very important.

Some years ago, one of us purified gold with great care and alloyed seventeen separate portions of it with foreign elements, in quantities which were in all cases close to 0·2 per cent., and from each sample of this alloyed gold, bars were cast 88 mm. long by 7·5 mm. wide by 5·2 mm. thick. The metal was in each case poured into a closed iron mould heated to about 500°; the cooling was, therefore, not very rapidly effected. The tensile strength, elongation, and reduction of sectional area (striction) were determined, and the results were published [8] in the *Philosophical Transactions* in 1888. [See Table on p. 270 of this volume.]

These results indicated, in a general way, that the tenacity and ductility of gold is increased by the presence of 0·2 per cent. of an added element of smaller atomic volume than that of gold itself, while on the other hand, these properties are diminished when the atomic volume of the added element is greater than that of gold. There are, as might be expected, exceptions and irregularities, but it is strange that they are not more numerous and more marked. The weight of the added element is in all cases close to 0·2 per cent., but the atomic percentage differs widely. It will be interesting to ascertain in a future research, what is the effect of adding to gold equal numbers of atoms of foreign elements.

[1] *Roy. Soc. Proc.*, vol. xxxviii. (1884-85), p. 488.
[2] *Roy. Soc. Phil. Trans.*, 1883, p. 32.
[3] *Ann. de Chim. et de Phys.*, vol. xii., 1844.
[4] *Roy. Soc. Phil. Trans.*, vol. cxxvi., 1866.
[5] *Bull. de l'Acad. Royale de Belgique*, vol. iv. (1882).
[6] *Phil. Mag.*, vol. xxxii., 1891, p. 41.
[7] *Chem. News*, vol. lxvi., 1892, p. 206.
[8] *Roy. Soc. Phil. Trans.*, vol. clxxix., 1888, A, p. 329.

The investigations which have been conducted in later years have revealed the complexities of the question. Even the purest metals are not, from a mechanical point of view, homogeneous. Under the influence of internal forces which tend to make them crystalline, and of external stresses which are set up by contraction during cooling, the invisible molecules become arranged in visible and more or less highly organised groups. These groups are separated from each other either by planes of cleavage or by joints which are often surfaces of least cohesion, and therefore of weakness. This is especially the case when these joints have been accentuated by the evolution of dissolved gas at the moment of the solidification of the metal.

In alloys, chemical homogeneity may, in turn, disappear, and free metals, chemical compounds, or various alloys, may fall out of solution from the liquid mass and finally the *eutectic* alloy solidifies, but the presence of a residual fluid facilitates the arrangement of the parts which have previously solidified.

One of us, in collaboration with M. Werth,[1] was probably the first to direct attention to the influence which these fusible residues, to which the name of "cements" was given, could exert on the working of steel and on the mechanical properties of the finished products. Since then, M. André le Chatelier [2] has repeatedly insisted on this point, correctly enough as a principle, though perhaps with a tendency to generalise too much from ideas which are in themselves accurate. The Reports of the Alloys Research Committee, organised by the Institution of Mechanical Engineers,[3] have, by the aid of autographic curves of the cooling of alloys, brought into prominence a certain number of instances of liquation in the cases of copper and silver, copper and bismuth, gold and aluminium, copper and tin.

Micrographs also reveal the existence of numerous constituents in a great number of alloys; in an alloy of 78 per cent. of gold with 22 of aluminium for instance, grains of a definite compound $AuAl_2$, of a brilliant purple colour, are separated by a fine network of a white alloy of very different composition,[4] and numerous other analogous examples are to be found in the work of Behrens,[5] of Guillemin,[6] of Charpy,[7] and others.

In short, we are led to distinguish in metals and alloys both the *visible* structure and the *molecular* structure, and, between these, such methods of investigation as are possible, enable a well-defined line of demarcation to be traced. Attention must, therefore, be directed to ascertaining to what extent the mechanical properties of a given sample of metal are due to each of these kinds of structure, and how far to such relations as are possible between them. This being the case, we considered that it would be interesting to submit the gold, containing 0·2 per cent. of various elements, to micrographical examination, and, fortunately, the identical specimens which were submitted

[1] Osmond and Werth, *Ann. des Mines*, vol. viii., 1885, p. 5.

[2] *Proc. Inst. Mech. Engineers*, April, 1893, p. 191.

[3] *Ibid.*, October, 1891, p. 543; April, 1893, p. 102; April, 1895, p. 238.

[4] This observation was not printed, but a diagram of the section was shown at a lecture delivered at the Royal Institution, 1891, and has been continuously used since by one of us in class teaching.

[5] "Das Mikroskopische Gefüge der Metalle und Legierungen," Leipzig, Voss, 1894.

[6] "Commission des méthodes d'essai des matériaux de construction," t. ii., p. 19.

[7] *Bull. de la Soc. d'Encouragement*, February, 1896.

by one of us to the Royal Society eight years ago had been preserved intact, and were available for examination.

Gold is a metal which may readily be purified to a high degree. It does not oxidise in air at any temperature. The influence of occluded gases appears to be small; and the quantity of the added element is in each case so small as to favour the view that, at least, most of the impurity remains dissolved throughout the mass without there being liquation either of definite or indefinite compounds. We have, in fact, reason to think that many disturbing causes are, if not eliminated, at least reduced to a minimum in this series of alloys. It will be possible up to a certain point to apportion the effect of these disturbing causes, and eventually to set aside such complications as tend to conceal the effect of atomic volume in the researches to which reference has been made.

With the exception of some facts stated by Behrens, and of some early experiments of our own, on the alloys of gold and aluminium, to which we have just referred, Prof. Arnold was the first to examine the alloys of gold. He took the experiments of one of us on the influence of impurities on the mechanical properties of gold as the basis of his work,[1] and made some careful drawings of etched sections of pure gold alloyed with about 0·2 per cent. of various impurities. We consider, however, that photographs of micro-sections are far preferable to drawings, and we agree with M. Charpy,[2] in thinking that drawings, however careful, give a very incomplete idea of the appearance of etched metallic surfaces. We have, therefore, great pleasure in submitting to the Society micro-photographs from the identical specimens of gold described by one of us in 1888, which formed the starting point for the later investigations. The results of the micrographic examination of these specimens of gold forms the first part of the present paper.

[Then followed a description of the methods of manipulation used in preparing the sections for microscopic examination, and of the means by which their appearances were photographically recorded. A detailed description was then given of the results afforded by micrographic examination.]

Conclusions.—We do not contest in any way, as our previous publications abundantly prove, the importance of the part which may be played in the mechanical properties of the alloys by the residues which remain liquid after the main mass of the alloy has solidified, the alloys being tested either at the ordinary temperature or when heated. But, in order that it may be possible for such cements to intervene and affect the mechanical properties of alloys, the cements must at least have a real existence. Nothing indicates that they do exist in ten out of twelve of our alloys, but we would not even express ourselves too positively on this point, for some new method of etching may reveal new facts. The impurities which are sought for may happen to concentrate themselves beyond the particular region which has been sectioned. These are, however, for the present gratuitous suppositions. Polishing only indicates the presence of cement in two cases. The little secondary crystals which we have already described might readily be mistaken for cements

[1] *Engineering*, vol. lxi., 1896, p. 176.
[2] *Bull. Soc. d'Encourage*, vol. i., 1896, p. 200.

of definite or indefinite composition if they were found only in certain specimens and then in such proportions as could be accepted. But we meet with them everywhere and in all cases their appearance is constant in forms and dimensions, and, moreover, we see them collect into crystallites which pervade the whole mass. These crystals are, therefore, usually and indubitably due to the crystallisation of gold itself, although the alloying substances sometimes (indium and probably potassium) join up the crystals in question. For the same reason the dark lines of the joints, traced as furrows by the etching, are very rarely the empty tracks of cement which has been dissolved away by *aqua regia;* their formation, which it is easy to follow in all its phases, directly connects them with secondary crystallisation. We are led to the belief that in the case of ten of our alloys of gold with about 0·2 per cent. of various impurities, solidification of the whole mass, although prolonged and less rapid than in the case of pure gold, has been directly accomplished without interruption, and that the foreign bodies have remained partly or wholly as *solidified* solutions, the impurities being dissociated into their atoms in both solid and liquid. We can at least say, without going beyond the actual evidence before us, that the dissemination of the foreign bodies eludes the power of the methods of investigation which we have employed. Under these conditions it is difficult to invoke, as explaining the mechanical properties of the alloy, the intervention of hypothetical cements with relatively low fusing points.

The absolute dimensions of the grains or crystallites cannot, as we have already seen, account for the mechanical properties. The micrographic examination of the copper-zinc alloys (brasses) has recently led M. Charpy [1] to a similar conclusion, and it is now certain that the large size of the grains does not, in itself, constitute a defective or an undesirable form of structure. If the metallurgy of steel points to a different conclusion, it is probably owing to the presence of gases which are often abundant and are apt to accumulate between the grains; these gases are the less divided, and consequently are the more dangerous, when the grains are large and the total surface of the joints is small for a unit of volume. Our attention has been specially directed to this point of M. Werth, who justly attaches great importance to the question of the presence of gas in steel.

The more or less advanced state of the crystallisation compared with the results of the tests for tensile strength does not show any direct relation.

Finally, micrographical examination only leaves us the joints themselves to account for the observed mechanical properties. Here the concordance is fairly good.[2] Without wishing to attribute a degree of precision which does not belong to them to the dimensions of joints which have been widened by etching, and perhaps modified to some extent by the longitudinal stress to which the bars were subjected, we can readily see, in a general way, that the thick and crystalline joints correspond to the alloys of low tenacity, while the converse is also true. But if the mechanical properties are in direct relation to the thickness of the joints and to the atomic volume of the alloyed

[1] *Loc cit.* He also shows that ordinary brasses may be effectively annealed at 500°.

[2] The alloy with indium is an exception, but we have verified the presence of cement, which has had, in this case, a favourable influence on the mechanical qualities.

elements, we may fairly conclude that a relation of cause to effect should exist between these two last variables.

This conclusion appears rather unforeseen. If we seek its interpretation, we are face to face with a very important but very complex question, that of the genesis of the joints in the metal.

A joint is often a surface of weakness, as we have already stated, in that it alone marks a sharp change of organisation and constitutes the artificial border of two natural groups. The more it diverges from a mathematical surface and acquires sensible thickness the weaker it becomes. How, then, is a joint formed? Evidently by an internal stress, if occluded gas, which appears negligible in the case of gold, be left out of the question. Such tractional stress is produced during solidification, cooling, and consequent shrinkage (and sometimes experimental proof of it is found in the presence of scraps of metal attached to the edges of a fissure). In order that a joint may be opened it is necessary (and it is enough) that the joint should be subjected, at a given moment, to a greater weight than its breaking strain, and that this breaking strain is less than the elasic limit of the metal in the interior of the grains.

We have then four factors at work:

1. The stresses established by the change of volume of the metal when it solidifies.

2. The stresses established by shrinkage, which themselves depend (the conditions of cooling remaining constant) on the coefficient of expansion of the metal.

3. The elastic limit and the "*deformability*" of the metal which forms the body of the grains.

4. The strength of the joint, which is *nil* towards the end of the solidification, and remains insignificant for a longer time if the solidification is prolonged by the presence of impurity. The presence of a crystalline envelope covering the joints, which appears to be an unfavourable condition, as it is specially marked in the alloys of low tenacity, is probably also connected with the prolongation or want of sharpness in solidification occasioned by the presence of certain foreign bodies. These envelopes without doubt represent the parts which have solidified last.

But all the factors we have just reviewed co-operate directly in determining the condition of the joints, and indirectly the mechanical properties of the cooled metal. The coefficient of expansion, the elastic limit, and plasticity of the bodies of the grains and the delayed solidification are directly dependent on the molecules and atoms. It is, therefore, not surprising that in a case which is relatively so simple as that of gold the influence of the atomic volume of the added elements can be directly observed. Furthermore, the relation between the mechanical properties of the metals and the atomic volume of the dissolved impurities is an experimental fact. We can now explain the greater part of the apparent exceptions. The exceptional behaviour of indium is explained by the presence of a cement, and that of lithium and of aluminium by the development of secondary crystallisation.[1] But as the conversion of heat into work is effected in the steam engine by a series of intermediate stages, so here also a more or less complex mechanism

[1] Zinconium still presents a very striking exception.

intervenes between the extreme terms which are in relation to each other. The foregoing research is a small contribution to the study of one of the elements of this mechanism.

Part II.—On Some Phenomena of Annealing.

Etching by sulphuric acid at a temperature of between 200° to 250° revealed a network of joints on the gold alloyed with bismuth and thallium, which the previous attack with *aqua regia* had not rendered apparent. All the specimens (except the alloy with indium which had not been subjected to the action of sulphuric acid) were then repolished and again etched with *aqua regia* under the same conditions as before.

The pure gold and the alloys with K, Pd, Zn, Rh, Li, Se, and Zr did not undergo any change, but the appearance of the four alloys with Bi, Tl, Sb, and Al were more or less altered by the treatment.

In the case of the bismuth alloy the large grains of the cast metal become subdivided, after heating for five minutes to between 200° to 250°, into a number of small polyhedral grains. The effect is just the same as is caused by annealing steel castings at a temperature of about 800°. Nothing remains of the original structures. In the new grains the paste, the secondary crystallisation, and the joints present the same characteristics as in the old grains.

The alloy with thallium undergoes a strictly analogous transformation, but the dominant lines of the initial structure were preserved in several places, notwithstanding the internal re-arrangement. The alloy with antimony behaved in a very different fashion. The original structure disappeared, but the new organisation showed neither the polyhedral grains nor the continuous network of joints; the incipient grains, indicated by the crystalline orientations, have not clean faces, and the sulphuric acid only traces fragments of broken joints. This structure recalls that of hardened steel of medium hardness.

The alloy with aluminium undergoes the same transformation, but only locally and partially. Generally speaking, it seems that bismuth, thallium, antimony, and aluminium, when present in the proportion of about 0·2 per cent., behave in respect to gold in the same way as carbon does with regard to steel, but at a much lower temperature.

It also appears to be evident that the bodies in question must have been present in the solid metal in a state closely resembling the fluid. None of these bodies possess a very high melting point, and, as is natural, this circumstance favours the maintenance of fluid molecules at a low temperature. The temperature, however, of annealing remains much below that of melting aluminium or antimony, and even below the melting points of the *eutectic* alloy of aluminium and gold (about 600°) or of antimony and gold (440°), and it at most reaches that of the fusion of bismuth. On the other hand, lithium, with a point of fusion below that of bismuth, and zinc with a fusing point below that of antimony, have not exerted a similar effect in lowering the temperature of annealing.[1] The melting point of the impurities, although it is not without influence, is not the sole factor to be considered. It should be observed that lead, judging from what is known of its action on gold,

[1] We are not speaking of potassium, which appears to be concentrated in a cement.

probably behaves like bismuth and thallium. Amalgamation also appears to be a phenomenon of the same kind, possibly occurring, owing to the liquidity of mercury, at a still lower temperature. But gold, mercury, thallium, lead, and bismuth follow each other in the classification of elements based on increasing atomic weight, and are grouped on the same horizontal line of Mendeléef's table. This coincidence is curious. Whatever it may signify, this transformation of the structure of a metal, at a temperature so far below its melting point, in the presence of only two-tenths per cent. of a foreign body, is probably not an isolated fact, and appears to open a new field for research.

ON THE MELTING POINTS OF THE GOLD-ALUMINIUM SERIES OF ALLOYS.

[*From the "Proceedings of the Royal Society,"* 1892, vol. l., pp. 367-368.]

The author has already described and exhibited to the Society a new alloy of gold and aluminium, $AuAl_2$, which is remarkable for its intense purple colour.

The physical constants of the gold-aluminium alloys are being determined, and the results will soon be ready for publication, but the series has been found to have one interesting peculiarity which deserves special mention. The author has shown (*Roy. Soc. Proc.*, vol. xlix., 1891, p. 347) that the addition of 0·2 per cent. of aluminium to gold produces an appreciable fall in the freezing point, an addition of 0·4 per cent. causing a fall of 14·28°, or an "atomic fall" of 5·0° C.

These facts indicated that it was desirable to ascertain what are the melting points of the gold-aluminium series of alloys generally, and this has now been done with the aid of the Le Chatelier thermo-couple used in the way which was previously described (*loc. cit.*).

The results show that, although a white alloy, containing 10 per cent. of aluminium, has a melting point which is no less than 417° lower than that of gold; the purple alloy, on the other hand, melts at a point which has yet to be definitely fixed, but which is several degrees above gold.[1] In fact, when workmen who are accustomed to melt gold on a large scale attempt to melt this purple substance, they find it difficult to believe that they are dealing with a gold alloy, as it is so infusible.

The melting points of the rest of the series richer in aluminium appear to fall continuously to 660°, a little below the melting point of aluminium (665° C.).

The purple alloy presents the only case, known to the author, of an alloy, free from mercury, having a higher melting point than that of the least fusible of its constituents, and he considers that this fact affords strong evidence of its being a true compound of gold and aluminium.

It is generally admitted that there are true compounds in the copper-tin series, for $SnCu_3$ and $SnCu_4$ seem to be well defined, but their melting points are much lower than that of copper.

A. P. Laurie has just shown (*Phil. Mag.*, January, 1892), that in the gold-tin series the alloy containing 63 per cent. of gold and 37 per cent. of tin has an electromotive force which distinguishes it from the rest of the series, and points conclusively to its being a true compound, but the author finds that it melts readily below redness.

[1] [Two very careful experiments were made, each with 40 grammes of the alloy, the cooling curve being traced by the autographic recorder already described (*Roy. Soc. Proc.*, *loc. cit.*). These curves gave 1,065° and 1,070° respectively as the melting point of the alloy $AuAl_2$, the mean of which is 32·5° higher than the melting point of gold. If, however, small quantities of the alloy be fused before the oxy-hydrogen blowpipe, it is easy to obtain a lower result, as aluminium is readily burnt out from the little mass. The composition of the alloy is thereby changed to one of the series richer in gold, of which the melting points are lower than that of gold.—Feb. 9, 1892.]

The melting points of ordinary chemical compounds are often much higher than the melting point of the least fusible constituent. *Galena*, for instance, melts at a strong red heat; it is difficult to fix the point accurately as the substance volatilises, but it is close to 900° C. Its constituents, lead and sulphur, melt at 335° and 115° respectively. *Stibnite* also, sulphide of antimony, melts at about 530°, according to Dr. Joly, while antimony fuses at 440°.

The gold-aluminium series is of unusual interest, and well deserves careful attention.

[The complete freezing point curves for the whole series of gold-aluminium alloys were subsequently obtained by Roberts-Austen, but these were not published, as the work was anticipated by that of Heycock and Neville.[1]]

[1] *Phil. Trans. Roy. Soc.*, vol. cxciv., 1900, A, pp. 201 232.

ON SURFUSION IN METALS AND ALLOYS.

[*From the "Proceedings of the Royal Society,"* 1898, vol. lxiii., pp. 447-454.]

Introduction.

The fact that metals and alloys may be maintained in a fluid state at temperatures which are many degrees below their true freezing points has been but little studied. As regards salts, the question of surfusion has recently received much attention. Ostwald [1] has shown, as the result of an investigation of great interest, that a very minute quantity of a solid will cause a mass of the same substance to pass from the surfused to the solid state. His work, moreover, has led him to distinguish between the *meta-stable*, or ordinary condition in which surfusion takes place, and the *labile* condition which occurs at temperatures much below the melting point. Ostwald's paper, and one by M. Brillouin,[2] on the theory of complete and pasty fusion lead me to offer the Royal Society the results of some experiments of my own on the surfusion of metals.

Historical.

Metals do not appear to have been studied from the point of view of surfusion until the year 1880, when some excellent experiments on the surfusion of gold were made by the late Dr. A. D. van Riemsdijk,[3] by whose early death, which occurred last year, Holland has lost a skilful physicist. He pointed out that :—

"Faraday, in his memoir on regelation, published in 1858, stated that acetic acid, sulphur, phosphorus, many metals and many solutions, may be cooled below the congealing temperature prior to solidification of the first portions." [4] On the other hand, in their treatises on physics, Danguin [5] and Jamin [6] mention tin as the only metal which is capable of remaining liquid at a temperature 2·5° below the true melting point of the metal, which is 228° C.

Van Riemsdijk's contribution to the subject of surfusion of metals consisted in showing that the well-known phenomenon of *éclair*, the brilliant flash of light which often attends the solidification of the metal in the ordinary assay of gold, is really due to surfusion. He also pointed out that surfusion could be either stimulated or hindered by suitably modifying the conditions, but he made no attempt at thermal measurements. It was not until ten years after the publication of van Riemsdijk's work that the recording pyrometer, which I devised and submitted to the Royal Society in 1891,[7] enabled such measurements to be readily effected.

The freezing point of a metal, or the initial freezing point of an alloy, for a fluid mass of two metals may possess many points of solidification,

[1] *Zeit. für Physikal. Chem.*, 1897, vol. xxii., p. 3.
[2] *Ann. de Chim. et de Phys.*, 1898, vol. xiii., p. 264.
[3] *Ann. de Chim. et de Phys.*, 1880, vol. xx., p. 66; *Nature*, vol. xxi., p. 531; and *Chem. News*, March 19 and June 11, 1880.
[4] "Experimental Researches in Chemistry and Physics," p. 379.
[5] Vol. i., 1855, p. 892. [6] Vol. i., 1859, p. 105.
[7] *Proc. Roy. Soc.*, 1891, vol. xlix., p. 347.

is represented by one or other of three typical curves. [These were shown in accompanying figures which indicated the nature of the curves, traced by the recording pyrometer. The first showed the freezing point curve of a pure metal, the horizontal portion indicating the actual solidification of the mass, the sharpness of the angles attesting the purity of the metal. The initial freezing point of most alloys would resemble this curve in having the first corner sharp, while the second point is generally rounded off. If the alloyed metals form an isomorphous mixture, neither angle is sharp, and in many cases there is no true freezing point, the curve being of the form represented by the freezing of the gold-silver alloy containing 28 per cent. of gold in which the fluid mass, as a whole, passes through a long pasty range before solidifying. The third type of curve, which may be a modification of the other two types, indicates the occurrence of surfusion, and shows the amount of surfusion which was observed.] I have detected pronounced cases of surfusion, not only in gold, but in copper, bismuth, antimony, lead, and tin. Surfusion, moreover, is not confined to pure metals, and I showed in 1893 [1] that the eutectic alloy in the bismuth-copper series presents a marked case of surfusion.

In order to study surfusion, it is necessary to make the galvanometer, to which the thermo-junction is attached, very sensitive, and, by suitable adjustment, it is easy to catch on the sensitised plate any desired portion of the range of the spot of light. It is, however, preferable to balance by a potentiometer the current which results from the heating of the thermo-junction, and in this way to prevent the mirror from swinging through a long range. The sensitiveness of the instrument is but slightly diminished by the introduction of the potentiometer. As the thermo-junction cools down, the spot of light from the galvanometer is simply made to traverse a short distance many times, instead of a long range once. The sensitised plate need only be exposed to the action of the spot of light at the critical moment, when solidification or surfusion is known to be imminent. A paper by my assistant, Mr. Stansfield, illustrating the use of this method, will shortly be published by the Physical Society.[2]

A curve, traced by the aid of either of the sensitive methods which have just been described, if it represents the surfusion of a metal or alloy, does not merely show a slight depression as in the case of pure gold: the slight depression becomes a deep dip. (Plate XXI., Fig. 1, which represents the surfusion of gold.) In this case three curves were taken on one plate, the line *ab* represents the heating and melting of gold, the horizontal portion marking the actual melting of the metal. The lines *cde* and *fgh*, on the other hand, represent successive coolings and solidifications of the metal, surfusion occurring in both cases, the horizontal portions at *e* and *h* representing the beginning of solidification of the gold in each case. It is noteworthy that these successive points of solidification differ by less than half a degree, the melting point of the metal (the line *ab*) occupying a median position between them. During the surfusion, the temperature of the metal fell about 2° below its true freezing point. Figs. 2 and 3, Plate XXI., both represent the

[1] "Second Report, Alloys Research Committee." *Mech. Eng.*, 1893, plate 32.
[2] *Phys. Soc.*, March 25, 1898; *Phil. Mag.*, July, 1898.

SURFUSION

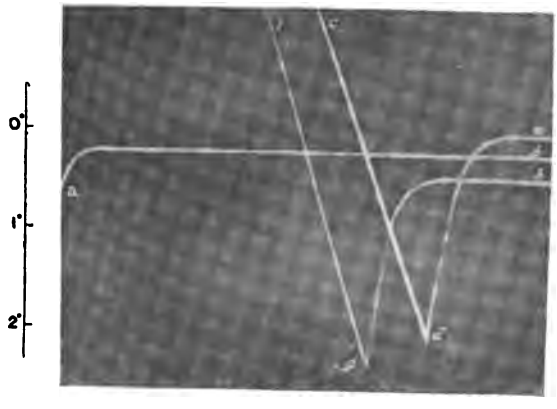


Fig. 1.—Gold.

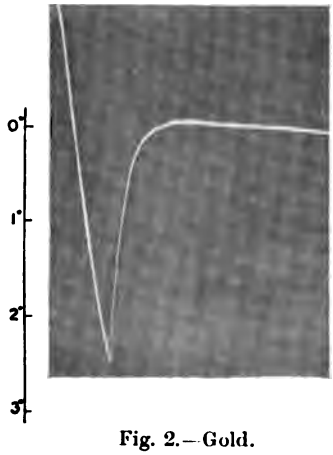


Fig. 2.—Gold.

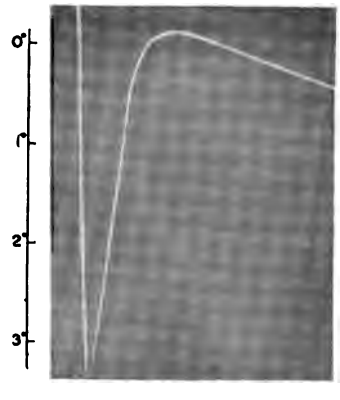


Fig. 3.—Gold.

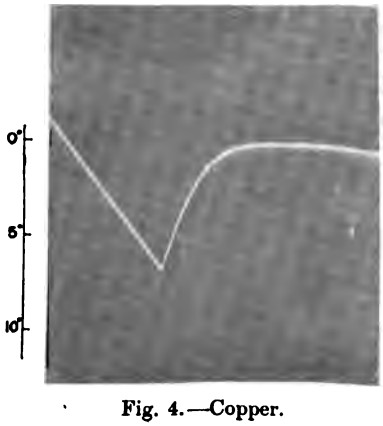


Fig. 4.—Copper.

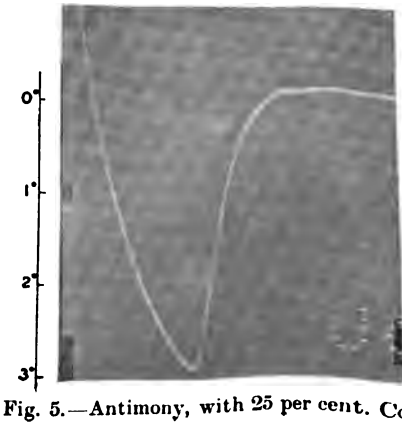


Fig. 5.—Antimony, with 25 per cent. Copper.

SURFUSION.

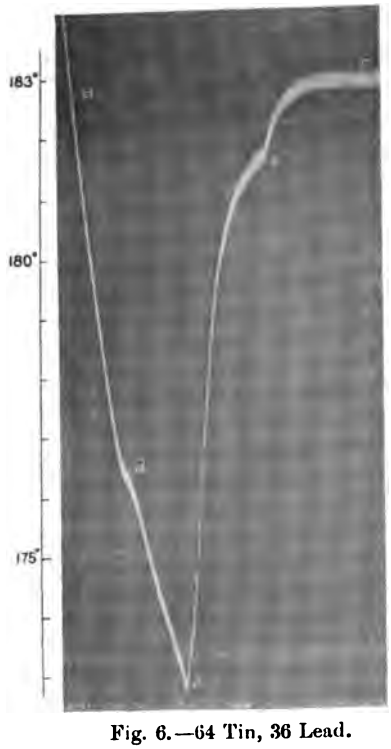


Fig. 6.—64 Tin, 36 Lead.

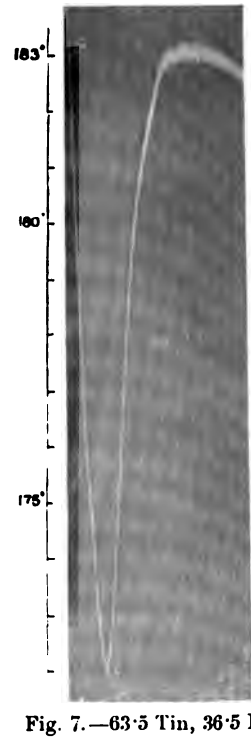


Fig. 7.—63·5 Tin, 36·5 Lead.

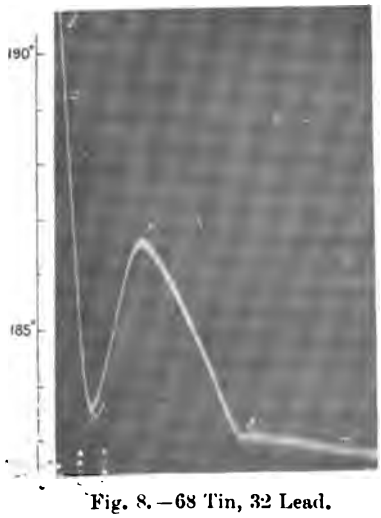


Fig. 8.—68 Tin, 32 Lead.

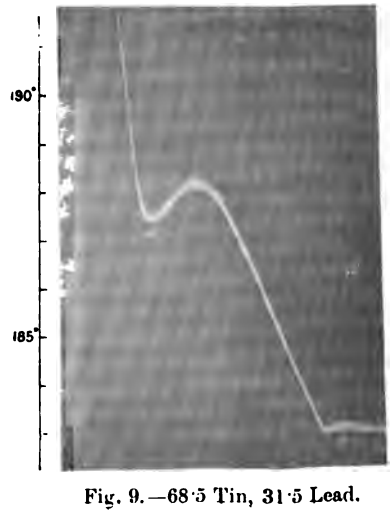


Fig. 9.—68·5 Tin, 31·5 Lead.

surfusion of gold; Fig. 4, Plate XXI., that of copper,[1] while Fig. 5, Plate XXI., represents the surfusion of an alloy of antimony with 25 per cent. of copper which freezes at 520°. It was selected as representing the highest temperature of surfusion which I have as yet examined in the case of an alloy. Such a surfusion curve, in the case of an alloy, may do much more than reveal the sudden release of the latent heat of the fluid mass. The curve may present a complicated record of modifications in molecular grouping occurring in the brief space of time actually occupied by surfusion. This is shown by the points *d*, *e*, in Fig. 6, Plate XXII., which represents the surfusion of tin alloyed with 36·5 per cent. of lead. All the curves on Plate XXII. serve as bonds connecting the behaviour of alloys with that of freezing solutions of salts.

The freezing point curve of the lead-tin series is a very ordinary type. It consists of two branches united at the point where they join a horizontal line which represents the freezing of the *eutectic* alloy of the lead-tin series. This alloy freezes at a constant temperature (183°). The eutectic constitutes a fluid residual "liquor" which is left after the excess of either lead or tin has fallen out as the mass cools down. When, however, the tin is present in slight excess of the amount required to constitute the eutectic, the whole mass of the alloy may remain fluid at temperatures below that at which the eutectic would naturally freeze. It may even cool to a temperature at which it can no longer maintain all its *lead* in solution, and some lead will, therefore, fall out while surfusion is actually taking place. This explains the existence of the point *d*, which marks an arrest in the fall of temperatures, in Plate XXII., Fig. 6 (on the line *ab*, representing the *fall* of temperature during surfusion). Conversely, when the surfusion is ended, the latent heat is released, and the line *bec* represents the *rise* of temperature due to the release of latent heat. There should also be on this line an indication of a retardation or arrest in the rise of temperature, because the lead which fell out of solution (at the point *d*) has to be re-melted. This point of arrest will be found at *e*.

In the same way, in Fig. 7, Plate XXII., which represents a fine case of surfusion in the lead-tin alloy containing 64 per cent. of tin, there is also a point at *f*, on the line *gh*, at which point the lead fell out of solution during the surfusion. Fig. 8, Plate XXII., represents the surfusion of a lead-tin alloy containing 68 per cent. of tin. In this case the tin is in large excess, and freezes first. In becoming solid, the tin would have been represented by a horizontal line somewhere about the point *s*, on the line *ij*, had not surfusion occurred, and been terminated by the solidification of tin at *k*. This is followed by the solidification of the eutectic mother liquor represented by the line *lm*. This eutectic does not surfuse because the tin (the metal in this alloy which is prone to surfuse) is already present in the crystalline form.

In Fig. 9, Plate XXII., a similar case is represented, but a small, though distinct, surfusion at the point *n* has been recorded. This surfusion at *n* probably indicates that the lead in the eutectic may surfuse slightly, even though the crystallisation of tin has begun.

By taking a series of lead-tin alloys which do not contain more than 2 or 3 per cent. of tin, in addition to the amount required to constitute the

[1] Figs. 2, 3, 4 on Plate XXI. were taken with an insensitive galvanometer, and have been enlarged by photography from the original plates. Fig. 5, Plate XXI., and all the curves on Plate XXII. are given exactly as they were taken on the plate of the recording instrument. The co-ordinates, as in the case of the Figs. 1 to 4, are time and temperature.

eutectic (62 per cent. of tin), the temperature at which the lead begins to crystallise below 183°, can be measured. The results are shown in the diagram, Fig. 3. In it the co-ordinates are temperatures and percentages of tin. Each alloy examined has, it will be seen, at least two freezing points, and some appear to have three, but in all the alloys one of the freezing points (the eutectic) is at the constant temperature 183°. In the eutectic alloy (62 per cent. of tin), theoretically these points *d*, *e*, should coincide. In Fig. 3 they are not quite coincident, and this is due to the fact that the lines AB, CD, drawn through the observed freezing points, are of necessity somewhat lower than the ideal solubility curves. The freezing points which lie below the horizontal or eutectic line were recorded while surfusion occurred. For instance, take the alloy containing 64 per cent. of tin, its initial freezing point would be at *a* 185°, that of its eutectic at *b* 183°, while the third freezing point, 176°, is due, as has already been explained, to the falling out of lead while the fluid mass was in the surfused condition. In order to observe the uppermost of the three points (185°), it is necessary to stir the mass to prevent the possibility of surfusion. On the other hand, a record of the

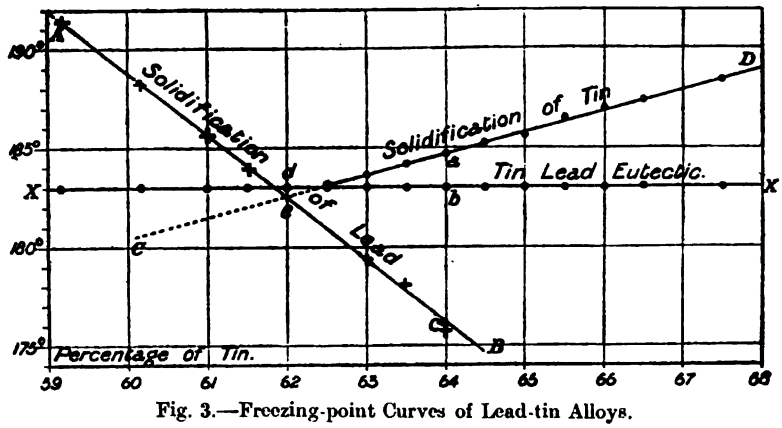


Fig. 3.—Freezing-point Curves of Lead-tin Alloys.

lowest freezing point can only be obtained in a fluid mass which is prefectly tranquil. When lines are drawn through all the points recorded it will be seen that the line AB representing the solidification of lead extends far below the horizontal line XX. It should be remembered that if the fluid mass is stirred, the first point to be recorded will be the upper or tin point (185°), followed by the eutectic point (183°). If the alloy surfuses, the first point recorded will be the lowest point (176°), followed in turn by the eutectic. In general, therefore, only two freezing points can be obtained in a single record.

In the case of salts the crossing of the curves of solubility has already been observed by H. le Chatelier and by Dahms, but in the case of alloys experimental evidence has hitherto been wanting. The silver-copper series presents many analogies to the lead-tin series. Heycock and Neville,[1] in their excellent work on the complete freezing point curves of many series of alloys, have calculated what the ideal freezing point curve of the silver-copper series would be, but the present paper affords, I believe, the first

[1] *Phil. Trans.*, A, vol. clxxxix. (1897), p. 25.

experimental evidence as to the identity of the behaviour of saline solutions and metallic alloys as regards selective surfusion.

Prolonged experience in these methods of manipulation may prove that it is possible to effect the separation of a particular metal or definite groups of metals by dropping in (during the surfusion of the fluid mass) a fragment of the same metal or of the particular group of the associated metals it is intended to separate. It is well known that the introduction of a fragment of the same metal or of an isomorphous metal or alloy will determine its solidification. Such a method may readily be employed in studying the surfusion of salts. In the case of metals, so far as my own experiments go, the surfused state is singularly unstable, for it may be disturbed even by very slight tremors. It remains to be seen whether it is possible to arrange the experiments in such a way as to maintain metals and alloys for an indefinite time in Ostwald's meta-stable condition which would need the presence of a particle of solid matter to induce the solidification of the mass.

Ostwald applies to the change from liquid to solid the equation which represents the gas-liquid change. In the former case there are, however, the three phases, solid, liquid, and gas, present, and a complete expression of the change must take account of all three. Thus during surfusion the gas phase is in equilibrium with the liquid phase, but when solidification has begun the gas phase must also be in equilibrium with the solid phase. It is possible that the solidification of the mass may be started by crystals deposited directly from its vapour, so that solidification of a surfused metal may be started by crystals from its own metallic atmosphere. The amount of gas evolved by a solid metal is, of course, very small. Evidence of the vaporisation of metals at very moderate temperatures is not wanting.

Demarçy [1] showed in 1882 that *in vacuo* metals evaporate at much lower temperatures than they do at ordinary atmospheric pressure. Pellat [2] pointed out that the proximity of the surface of a metal to that of another metal in air changes its electrical condition, and he attributed this to vaporisation of metals, showing that even iron exerted an influence at a distance. Colson [3] showed that a photographic plate was affected by the vapour of certain metals, notably by zinc, cadmium, and magnesium, even through porous septa. Dr. Russell [4] in some recent and very interesting experiments, was led to the conclusion that even so infusible a metal as cobalt will by vaporisation affect a photographic plate. In January, 1897, before hearing of Dr. Russell's experiments, I began some experiments with a view to ascertain whether metals, vaporised *in vacuo* near the ordinary temperature, will actually unite to form alloys. I found that when cadmium and silver were opposed for eight days at a temperature of 50° an appreciable deposit of a tinted cadmium-silver alloy formed on the surface of the silver.

The results given in the present paper reveal additional points of similarity between the behaviour of alloys and that of ordinary saline solutions. I trust, therefore, that it may be useful as a continuation of my investigation on the "Diffusion of Metals," which formed the subject of the Bakerian Lecture of 1896.

[1] *Comptes Rendus*, 1882, vol. xcv., p. 183.

[2] *Comptes Rendus*, 1882, vol. xciv., p. 1247; 1896, vol. cxxiii., p. 104; and 1898, vol. cxxvi., p. 1338.

[3] *Ibid.*, 1896, vol. cxxiii., p. 49.

[4] *Roy. Soc. Proc.*, 1897, vol. lxi., p. 424, and *ibid.*, vol. lxiii., p. 102, Bakerian Lecture, 1898.

BIBLIOGRAPHY OF ROYAL SOCIETY PAPERS.

1875. On the Liquation, Fusibility, and Density of certain Alloys of Silver and Copper.—*Proceedings*, clxii., pp. 481-495.

1888. On certain Mechanical Properties of Metals considered in Relation to the Periodic Law.—*Phil. Trans.*, clxxix., pp. 339-349. *Proc. Roy. Soc.*, xliii., pp. 425-428 (abstract).

1891. On certain Properties of Metals considered in Relation to the Periodic Law.—*Proceedings*, xlix., pp. 347-356 (with figures).

1892. On the Melting Points of the Gold-Aluminium Series of Alloys.—*Proceedings*, l., pp. 367-368.

1896. On the Diffusion of Metals—Bakerian Lecture.—*Phil. Trans.*, clxxxvii., pp. 383-415, 2 plates. *Proceedings*, lix., pp. 281-285 (abstract).

Alloys formed by Diffusion. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 383-415.

Diffusion of Metals, Solid and Liquid, Constants of. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 383-415.

Gold, Diffusivity of, in Lead, etc. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 383-415.

Lead, Diffusivity of Metals in Liquid and Solid. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 383-415.

Metals, Fluid and Solid, Diffusion of. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 383-415.

Molecular Movement in Liquid and Solid Metals. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 383-415.

Osmotic Pressure in Liquid Metals and Solid Metals. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 383-415.

1896. On the Structure of Metals, its Origin and Changes. (In collaboration with F Osmond.)—*Phil. Trans.*, clxxxvii., pp. 417-432, 1 plate.

Alloys of Gold, Annealing at Moderate Temperatures. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Alloys of Gold, Mechanical Properties of. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Annealing Alloys of Gold. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Atomic Volume, Influence of, in Relation to Gold Alloys. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Crystallisation of Alloyed Gold. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Gold, Alloyed, Effect of Annealing. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Gold, Alloyed, Micro-structure of. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Gold, Alloyed, Tenacity of, varies with Alloying Element. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Metals, Origin of Structure in. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Micro-structure of Alloyed Gold. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Solutions Solidified, Gold Alloys considered as. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

Tenacity of Gold Alloys. *Phil. Trans.*, A, 1896, vol. clxxxvii., pp. 417-432.

1898. On Surfusion in Metals and Alloys.—*Proceedings*, lxiii., pp. 447-454, 2 plates.

1900. On the Diffusion of Gold in Solid Lead at the Ordinary Temperature.—*Proceedings*, lxvii., pp. 101-105.

1900. On certain Properties of the Alloys of the Gold-Copper Series. (In collaboration with T. K. Rose.)—*Proceedings*, lxvii., pp. 105-112, 1 plate.

1902. On certain Properties of the Alloys of the Gold-Silver Series. (In collaboration with T. K. Rose.)—*Proceedings*, lxxi., pp. 161-163, 1 plate.

1875. On the Absorption Spectra of Metals volatilised by the Oxy-hydrogen Flame (In collaboration with Norman Lockyer.)—*Proceedings*, xxiii., 1875, pp. 344-349. *Phil. Trans.*, cxiv., p. 495. *Phil. Mag.*, i., 1876, pp. 234-239.

1873. On the Quantitative Analysis of certain Alloys by means of the Spectroscope. (In collaboration with Norman Lockyer.)—*Phil Trans.*, clxiv., pp. 495-499, 1 plate. *Proceedings*, xxi., 1873, pp. 507-508.

VII.

ROYAL INSTITUTION LECTURES.

Certain Properties common to Fluids and Solid Metals, 1886—Some curious Properties of Metals and Alloys, 1888—Metals at High Temperatures, 1892—The Rarer Metals and their Alloys, 1895—Metals as Fuel, 1901.

ON CERTAIN PROPERTIES COMMON TO FLUIDS AND SOLID METALS.

Friday, March 26, 1886. *Proc. Roy. Inst.*, 1886, vol. xi., p. 395.

In one of the beautiful discourses, delivered in the early part of the last century, which grace the annals of the French Academy of Sciences,[1] Réaumur observes that industrial art, like nature, has its marvels, which we often fail to notice because they are constantly before us.

The extraordinary ductility of metals appeared to him to involve one of the deepest secrets of nature, and although he held that in his time science was hardly in a position to explain more fully than the old philosophers did, the cause of this property of bodies, it was nevertheless possible to see better than they, what advantage art has gathered from the power of leading and guiding metals by hammering or by traction, and from this point of view, both art and nature seem, he says, to rival each other in furnishing us with remarkable facts. Réaumur then, with singular clearness, defines the conditions under which metals prove to be ductile. The relation between the behaviour of solid metals and fluids has long been recognised, not merely in the sense that atomic motion is common to solids and fluids, and that, therefore, "everything moves and nothing remains," but apart from theory there is much experimental evidence as to the properties that are common to fluids and solid metals, the characteristics of which, at first sight, seem widely separated. Let me remind you of the elementary definition of the two states, *solid* and *liquid*. A solid has a definite external form which either does not change, or only changes with extreme slowness when left to itself, and, in order to change this form rapidly, it is necessary to exert a more or less energetic effort. A liquid, on the other hand, can be said to have no form of its own, as it always assumes that of the containing vessel, the mobility of its particles is extreme, its resistance to rupture is very small, and its free surface is always a plane when the mass is left at rest. Then there is the colloid condition, which intervenes between the liquid and crystalline solid state, extending into both, and probably affecting all kinds of solid and liquid matter in a greater or less degree. The colloid or jelly-like body does present a certain amount of resistance to change of shape. Such a

[1] "Histoire de l'Academie Royale des Sciences," 1713 (vol. for 1739, p. 199).

substance is well imitated by a skin of thin india-rubber filled with water. Another illustration is probably afforded by iron and other substances which soften under heat, and may be supposed to assume, at the same time, a colloid condition. Lastly, there is the gaseous condition of matter, with which we have but little to do at present.

We are in the habit of regarding metals as typical solids. I hope to trace this evening the analogies of their behaviour under certain conditions with that of fluids, and the following list shows the order in which I propose to group the properties common to fluids and solid metals :—

1. Rejection of impurities on solidification.
2. Surfusion.
3. Flow under pressure.
4. Changes due to compression.
5. Absorption of gases.
6. ,, liquids.
7. Diffusion.
8. Vaporisation.
9. Surface tension.

The transition from the liquid to the solid state is marked by the same phenomena in the case of many metals, as is observed in certain fluids, and I must dwell on this very briefly as leading up to the relations between solid metals and fluids, which come more definitely within the title of the lecture.

Water on passing from the liquid to the solid state undergoes a partial purification, the ice first formed being sensibly more free from colouring matter or suspended particles than the water from which it separates.

Many metals on freezing similarly eject impurities. In the case of alloys, saturated solutions, of one metal in another, appear to be formed, and excess of metal ejected, a fact which is being studied with much care by my colleague, Dr. Guthrie. The prominent facts are perhaps best illustrated by reference to a frozen mixture of copper, antimony, and lead. The results of some experiments conducted in my laboratory by my assistant, Dr. E. J. Ball, show that when a molten mixture of these metals is solidified, a definite atomic alloy of copper and antimony, which possesses a beautiful violet tint, first forms, and, after saturating itself with lead, up to a certain point, it ejects the rest of the lead, driving it to the centre of the mass so as to form a sharp line of demarcation, presenting a direct analogy to the ice, which is comparatively colourless, first forming from coloured water. Then there is another remarkable analogy between the freezing of certain fluids and the solidification of some metals. Water, as is well known, may be cooled down to $-8°$ C., without solidification, but agitation immediately determines the formation of ice, and at the same time a thermometer plunged in the water rises to zero. Faraday stated, in 1858, that fused acetic acid, sulphur, phosphorus, many metals and many solutions,[1] would exhibit the same effect. Tin also may be cooled to several degrees below its solidifying point without actually freezing, and Dr. van Riemsdijk,[2] of Utrecht, has observed that a globule of gold or silver, in a fused state, will pass below its solidifying point

[1] Faraday, "Experimental Researches in Chemistry and Physics," p. 379.
[2] Dr. Van Riemsdijk, *Ann. de Chim. et de Phys*, t. xx., 1880, p. 666.

without actually solidifying, but the slightest touch with a metallic point will cause the metal to solidify, and the consequent release of its latent heat of fusion is sufficient to raise the globule to the melting point again, as is indicated by a brilliant glow which the button emits, a beautiful effect which I hope to show you. [The experiment was then made.]

It may be well also to remind you incidentally that a minute variation in composition is sometimes sufficient to lower the melting point of a metal or alloy, as is instanced by the addition of $\frac{2}{10}$ per cent. of silicon to standard gold, which, as you will observe in the case of this strip of the alloy, softens in the flame of a candle, or at about the melting point of zinc, 412° C., although the melting point of standard gold, free from silicon, would be over 1,000° C.

Now to pass to solid metals. It is the common experience of us all, that a counterfeit shilling, consisting principally of lead, does not "ring" when thrown on a wooden surface. In 1726, Louis Lemery observed that lead is under certain conditions almost as sonorous as bell-metal.[1] He communicated the fact to Réaumur, who, being much struck by it, investigated the conditions under which lead becomes sonorous, and submitted the results to the French Academy.[2] He pointed out that in describing a body which is not sonorous, it is usual to say that it as "dull as lead," an expression which has become proverbial. "Nevertheless," he adds, "under certain conditions, lead has a property both novel and remarkable, for it emits surprisingly sharp notes when struck with another piece of lead." He showed that it was necessary that the lead should be formed by casting into a segment of a sphere, that is, mushroom shaped, as in the specimens of lead exhibited. The lead must be free from prominences, and must be neatly trimmed. The effect is less marked, if the lead be very pure, than if ordinary commercial lead be used, but it is only a question of degree.

[A mass of pure lead cast into the shape indicated above was struck with a piece of lead, and it emitted a sharp, clear note.]

I have shown you the experiment mainly for the sake of being able to quote Réaumur's observations upon it. He showed that the sonorous lead might be rendered dull by hammering it. Here is lead from the same sample of metal as that from which the sonorous mass was cast, but it has been flattened out, and you will observe that it is "dull." I think his remarks have been overlooked in late years. He was led to the belief that in cast lead there must be an arrangement of the interior of the mass which the hammer cannot impart, because lead fashioned by hammering into the same form as the sonorous cast mass, is dull, and, more important still, he held that the fibrous and granular structure of the lead is modified in a manner which makes it probable that the sound is due to the shape of the grains, and to the "way in which they touch each other"; further, the blows of the hammer not only change the arrangement of the fibres, but they alter the shape of the grains, "the round grains are rendered flat, they are compelled to elongate and fill the interstitial spaces which previously existed between them. The particles are no longer free to vibrate, hence the lead is dull." These remarks derive additional interest, if we compare them with the observations of Prof. Osborne Reynolds' most important lecture on "Dilatancy in Granular Matter" recently delivered here. We shall also,

[1] Hoefer, "Histoire de la Chimie," t. ii., p. 374.
[2] "Histoire de l'Academie Royale des Sciences," Anné, 1726, [vol. for 1728, p. 243].

I think, see that this description of Réaumur's shows that he fully appreciated the theoretical importance of the kind of facts depending on the transfer of metallic matter from one position to another, which we now consider to be characteristic of the "flow" of metals; at any rate I have thought it well to make Lemery's experiment the starting point of the rest of the remarks I have to offer you.

A solid may be very brittle, and may yet, if time be given to it, flow from one point to another. This stick of sealing-wax was supported at its ends, and it has in a few weeks bent at the ordinary atmospheric temperature, although at any given point of its flow it would have been easy to snap it with a slight application of force. This much thinner strip of pure lead of the same breadth as the sealing-wax, also bends at the ordinary temperature with its own weight, the ends being supported. Sir William Thomson has pointed out that a gold wire sustaining half the weight which would actually break it, would probably not rupture in a thousand or even a million years, that is to say, there would be no "flow" ending in disruption; if, however, force be suitably applied, metals will flow readily. First, let us examine the case of a metal under force applied so as to compel it to flow through a hole, and I would point to the analogy of an ordinary viscous fluid. This vessel containing treacle is provided with a cylindrical hole in its base, and on the removal of the plug which now closes it, the treacle will flow out, the end of the stream being rounded. If a similar vessel be filled with lead it will, at the ordinary pressure, remain there, but if pressure be applied the lead will prove by its behaviour that it is really a viscous solid, as it flows readily through the orifice; the end of the jet is rounded, and, as has been shown by the beautiful researches of the late M. Tresca, of Paris,[1] all the molecules which compose the original block place themselves in the jet absolutely as the molecules of a flowing jet of a viscous fluid would. If the metal has a constant "head," as it would be termed in the case of water, that is, if the vessel be kept filled with solid lead up to a certain level, then you have a continuous stream, the length depending on the constancy with which the "head" and the pressure are maintained. If, on the other hand, the head is diminished so that nearly all the solid lead has been allowed to flow away, you have a folding of the jet, and vertical corrugations, exactly such as would characterise the end of the flow of certain other viscous fluids, and finally the jet forms a distinct funnel-shaped tube, concentric with the jet. It is also seen that when the formation of these cavities takes place, the jet is no longer equal to the full diameter of the orifice, the formation of the contracted vein is manifest, and a new analogy is thus obtained between the flow of solids and liquids. The application of this fact, that solid metals flow like viscous fluids, is of great importance in industry, and the production of complicated forms by forging or by rolling iron and steel and other metals, entirely depends on the flow of the metal when suitably guided by the artificer. The lines of flow in iron may be well shown by polishing a surface of the metal, and by submitting it to the action of a solution of bichloride of mercury, which etches the surface, or better, to the slow action of chromic acid solution,

[1] These researches extend through a long series of memoirs: those relating to the flow of metals are well summarised in the *Proceedings Inst. Mech. Engineers*, 1867, p. 114, and in the report of the Science Conferences held in connection with the Loan Collection of Scientific Apparatus (Physics and Mechanics), London, 1876, p. 252.

as suggested by Sir Frederick Abel, the result in either case being, that any difference in the hardness of the metal or in the chemical composition, or want of continuity, caused by the presence of traces of entangled slag, reveals the manner in which the metal has flowed.

A very striking illustration of the importance of the flow of metals, when used in construction, is afforded by some observations of Mr. B. Baker, in a recent paper on the Forth Bridge.[1] He says, "If the thing were practicable, what I should choose as the material for the compression members of a bridge, would be 34 to 37-ton steel, which had been previously squeezed endwise, in the direction of the stress, to a pressure of about 45 tons per square inch, the steel plates being held in suitable frames to prevent distortion." He adds, "My experiments have proved that 37-ton steel so treated will carry as a column as much load as 70-ton steel in the state in which it leaves the rolls, that is to say, not previously pressed endwise. . . . At least one-half of the 42,000 tons of steel in the Forth Bridge is in compression, and the same proportion holds good in most bridges, so the importance of gaining an increased resistance of 60 per cent. without any sacrifice in the facility of working, and safety belonging to a highly ductile material can hardly be exaggerated." I need not point to the extreme interest, in connection with my subject, of these remarks from so distinguished an authority.

The very ancient mechanical art of striking coin is wholly dependent on the flow of metals. There is a popular belief that the impression imparted to discs of metal during coinage, is merely the result of a permanent compression of the metal of which the disc is made. Striking a coin, however, presents a case of moulding a plastic metal, and of the true flow of metal, under pressure, into the sunk portions of the die. I once heard Mr. Ruskin say: "You stamp the figure of the cow on a pat of butter; why do you not impress the bee on honey?" Simply because honey is not plastic and is too viscous, and it flows at the ordinary atmospheric pressure. This medal, struck from a series of discs, will serve to show, when the discs are separated, the way the metal flows into the deepest portion of the die. If the alloy used be too hard, or if the thickness of the metal required to flow be insufficient, the impression will always be defective, no matter how many blows may be given by the press. In Mr. Browning's well-known poem, "The Ring and the Book," there is a subtle recognition of the viscous nature of very pure gold, which he characterises as "the oozing of the mine." while, with regard to the manufacture of the ring, he shows—

> "Since hammer needs must widen out the round
> And file emboss it fine with lily flowers,"

that this is only possible because gold behaves like the honey to which he compares it. I have chosen this reference to Browning because I happen to have a coin of "the great Twelfth Innocent," the Pope of the poem I have cited, and this coin has scars on its surface which prove that there was not quite enough metal to flow into the depths of the die.

If one side of the coin be ground away so as to leave a flat surface, and if the disc be then struck between plain polished dies surrounded by a steel collar, so as to prevent the escape of the metal, the impression on the disc

[1] *Journ. of the Iron and Steel Inst.*, vol. ii., 1895, p. 497.

will be driven through the thickness of the metal, and will then appear on both sides. In industrial art the property of flow of metals is very important. The "spinning" of articles in pewter is a familiar instance, and one which I propose to illustrate.

[A disc of pewter was spun, on a lathe, into a vase, the shadow being projected on the screen during the operation.]

The production of complicated forms, like a jelly mould, from a single sheet of copper under the combined drawing and compressing action of the hammer, is a still more remarkable case.

The flow of metals is illustrated very curiously in one phase of Japanese art metal work, of which, however, it is now so difficult to obtain native examples, that I have been obliged to prepare, with the aid of skilful artificers in the Mint, the few specimens I have to submit to you. I allude to the metal work in banded alloys to which the Japanese give the name of Moku-me, or "wood-grain." In its preparation thin layers of copper, precious metals, and various alloys, are soldered in superposition like the leaves of a book; through these layers holes are drilled to varying depths in the thickness of the metal, or trenches are cut in it. The mass is then hammered flat until the hole or trenches disappear, and the result is contorted bands, of some complexity, and often possessing much beauty, especially when the colour of the metal is developed by suitable chemical treatment and polishing. A similar effect may be produced by beating up the metal from one side, and filing the other flat. The structure depends on the flow of the respective metals of which the mass is composed, and behaviour of the components of the system, and suggests one of the most marked facts in experimental hydrodynamics, namely, the difference in the way in which water flows along contracting and expanding channels. The sinuous lines the metal assumes in the preparation of Moku-me, resemble the beautiful illustrations devised by Prof. Osborne Reynolds, to show the flow of water.

We have hitherto only considered the flow of metals when submitted to compression, let us now examine the effect of traction. When a viscous metal, such as iron or soft steel, is submitted to stress by pulling its ends in opposite directions, it stretches uniformly throughout its length; there is in such a solid, a limit in the application of the stress up to which the metal, if released, will return to its normal length; this point is the limit of elasticity. Directly, however, this limit is reached, the metal begins to stretch, and at first it stretches in a very singular way, without an increase of load; when the limit of elasticity has been passed, the metal continues to stretch with increased load until it gives up resisting and breaks. The limit of elasticity of a solid body marks the moment at which the body begins to "flow" under the influence of the force to which it is submitted. There are many materials which do not stretch when their limit of elasticity is reached: in very hard steel, for instance, the breaking point and the limit of elasticity practically coincide. Further, it must be observed that every minute variation in composition is sufficient to change the property of a body, and to cause what was a viscous body to break close to the limit of elasticity. A most remarkable instance is presented by certain alloys of gold and copper. Standard gold, such as is employed for British gold coin, which contains 9,167 parts of gold in 10,000 parts, breaks with a load of 18 tons to the square inch. Its limit of elasticity is reached at 1¾ tons per square inch, but it elongates 34 per cent.

before it breaks. If this standard gold has only the $\frac{1}{2000}$ part of lead added to it, it becomes very brittle, and breaks with a stress of about 5½ tons to the square inch, instead of 18 tons borne by the original pure standard gold, and as it does not elongate sensibly it cannot be said to flow at all. A remarkable difference in the property of the alloy, standard gold, is, therefore, caused by the addition of only the $\frac{1}{2000}$ part of lead. In order to understand this it will be necessary to trace the analogy between fluids and solid metals still further, and to ascertain what takes place when metals, in a roughly granular state, are submitted to compression, under conditions in which the escape of the compressed metal is, as far as possible, restrained. I must, therefore, turn to what I believe to be the most important work relative to the molecular constitution of metals, which has been done for many years, namely, the researches of Prof. Walthère Spring, of the University of Liége, whose labours have since 1878 been devoted to the study of the effect of compression on various bodies.[1] The particles of a metallic powder left to itself at the ordinary atmospheric pressure, will not unite; by "augmenting the number of points of contact in a powder," the result may be very different. The powders of metals may weld into coherent blocks.

The more interesting results were obtained by Spring with crystalline metals. Bismuth is, as is well known, very brittle and crystalline, yet fine powder unites under a pressure of 6,000 atmospheres into a block very similar to that obtained by fusion, having a crystalline fracture. The density of compressed bismuth is 9·89, identical with that of metal which has been fused. The table shows the amount of pressure required to unite the powders of the respective metals:—

	Tons per sq. inch.
Lead unites at	13
Tin "	19
Zinc "	38
Antimony unites at	38
Aluminium "	38
Bismuth "	38
Copper "	33
Lead flows at	33
Tin "	47

We will endeavour to repeat M. Spring's results in the case of bismuth. It is necessary that the powder be perfectly clean and dry, if it be then submitted *in vacuo* to a pressure of 6,000 atmospheres, it will weld into a crystalline mass.

We know that combinations are produced when certain bodies in solution are submitted to each other's action. But do solids combine? Is the alchemical aphorism that bodies do not react unless they are in solution, true? Experiment proves that such solution is not necessary. I have here two anhydrous salts, iodide of potassium and corrosive sublimate, and they are at the same time dry; when they are mixed together in this mortar, they unite, as is shown by the vermilion colour which is produced.

My colleague, Prof. Thorpe, called attention to the importance of this

[1] *Bull. de l'Acad. Royal de Belgique*, (2) t. xlv., No. 6, 1878; (2) t. xlix., No. 5, 1880. See also subsequent papers in the same publication, in the *Bull. Soc. Chim.*, Paris, and in the *Deutsche Chemische Gesellschaft* (Bildung von Legirungen durch Druck), b. xv., p. 595.

fact at the meeting of the British Association at York, 1881. But do solid metals combine in the sense, that is, in which chemical combination is possible between the metals, when submitted to each other's action? We know that metals do combine if they be fluid, and the extraction of gold and silver from their ores by amalgamation is moreover easy.

It occurred to M. Spring that if there be a true union between the particles of a metallic powder, when submitted to great pressure, it ought to be possible to build up alloys by compressing the powders of their constituent metals, and he urged that the formation of alloys by pressure would afford the most conclusive proof that there is a true union between the particles of metals in the cold, when they are brought into intimate contact. Experiment proved that this reasoning was correct, for by compressing, in a finely divided state, fifteen parts of bismuth, eight parts of lead, four parts of tin, and three parts of cadmium, an alloy is produced which fuses at 100° C. It is necessary, however, to compress the mixed powders twice, crushing or filing up the block obtained in the first compression, because the mechanical mixture of the constituent metals is not sufficiently intimate to enable a uniform alloy to be obtained by a single compression. The alloy we have thus produced fuses, you will observe, in boiling water, actually at 98° C., although the melting point of the most fusible of its constituents, the tin, is 228° C. I agree with Prof. Spring in thinking that the formation of alloys by pressure affords the most complete proof which can be given of the accuracy of the views he has adduced.

The formation of fusible metal by compression leads me to deal with an objection which may, no doubt, have suggested itself to many of us. It may be urged that by compressing these metallic powders heat is evolved, and that this heat may be sufficient to produce incipient fusion in the metallic powders, or, at all events, may exert a material influence on the result obtained. This objection has been experimentally anticipated by Prof. Spring. First, the compression is effected with extreme slowness, and therefore there can be no question as to the sudden evolution of heat, as would be the case if the powders were compressed by impact instead of by a slow squeeze; and to sum the matter up briefly, Spring calculates, taking an extreme case, that, if it be granted that all the work done in compressing the powders were actually translated into heat, it would only serve to heat a cylinder of iron 10 mm. in height and 8 mm. in diameter (the dimensions of cylinder produced in his apparatus), 40·64° C. In order that direct experimental evidence might not be wanting, Spring took the organic body phorone, a hard crystalline substance which melts at 28° C., and compressed it exactly as in the case of the metallic powders.[1] He took the precaution to place a shot of lead on the top of the powder before submitting it to compression: only imperfect union of the particles of phorone resulted. The conclusion of the experiment proved that the shot remained where it had been placed at the top of the column, and therefore the 28° necessary to melt the substance had not been evolved, for if it had the shot must have fallen through the fluid mass. I think, then, it is absolutely safe to conclude that, in the compression of bismuth, for instance, there can be no question of the evolution of the heat necessary for the fusion of the metal.

There is, however, other evidence to which I may incidentally appeal. M. Spring has shown that by compressing powders together, chemical com-

[1] *Bull. Soc. Chim.*, Paris, 1884, t. xli., p. 488.

bination may be induced, and he has in this way produced arsenide and sulphide of zinc, sulphide of lead and of bismuth, and arsenide of lead. These are not merely intimate mechanical mixtures. Take, for instance, the sulphide of magnesium produced by compression; it is soluble in hot water; treatment with dilute hydrochloric acid evolves sulphuretted hydrogen, which is not the case with mere mixtures of magnesium and sulphur. Further, Spring has shown that by pressure a body may be made to pass from one allotropic state to another. Plastic sulphur is, under a pressure of 6,000 atmospheres, compelled to pass into the condition of octahedral sulphur, an allotropic state which possesses a greater density. And he points out that a solid metal (not powders of metals) may have cavities obliterated by pressure, but that matter cannot be permanently compressed by pressure, unless it can assume an allotropic state of greater density than the one it possesses at the moment of compression.[1]

Now let me point to the evidence these experiments afford as to the relation between solid metals and fluids. Members of the Royal Institution will know that Faraday discovered, in 1850, that two fragments of ice pressed against each other will unite, tendency to their union being considerable when the fragments are near their melting point. We also know what splendid service the regelation of ice has afforded in the hands of Dr. Tyndall, in explaining the formation of glaciers. Ice owes its movement, not to viscosity, but to regelation, and the union of fragments of ice under compression is also due to regelation. The facts which have been appealed to, and the theories which have been formed, respecting the regelation of ice, are too well known to you to demand lengthy notice from me. I will only observe that bismuth, like ice, expands on solidifying, and although Faraday failed to establish the existence of a property similar to regelation in bismuth, an eminent engineer, Mr. Thomas Wrightson, to whom we owe a series of experiments on the fluid density of metals, has satisfied himself by experimental evidence, that regelation exists in bismuth. Now, in explaining Spring's results we are met by this difficulty; the union of the particles of the metals cannot, in all cases, be due to viscosity, because viscous bodies are always capable of being stretched, and we find the welding taking place between the compressed powders of bodies such as zinc and bismuth, which, when submitted to traction, will not stretch.

Spring, therefore, asks, "Is it possible that regelation may have something to do with the union of the powders?" and he urges, "Is it safe to conclude that regelation is peculiar to water alone?" "It is difficult to believe," he adds, "that in the large number of substances which nature presents to us, but one exists possessing a property of which we can find only minute traces in other bodies. The sum of our chemical and physical knowledge is against such a belief, and therefore the phenomenon of regelation may be pronounced in ice without being absolutely wanting in other bodies. To ascertain whether this is so, it is necessary to submit various bodies to the conditions under which the phenomena can be produced." "What," he asks, "are these conditions?" and he answers, "The pressure supported by the body, a certain degree of temperature, and time."

Helmholtz and Tyndall have shown that when the pressure is weak,

[1] Sur l'elasticité parfaite des corps solides chémiquement définis." *Bull. Acad. Roy. Belgique* (3), t. vi., 1883.

the regelation of ice is effected slowly. Spring points out that nitrate of sodium and phosphate of sodium, in powder, left to themselves in bottles become coherent, and if the coherence in these and other chemical compounds is but weak, it is simply because the points of contact between the particles of powder are but few. If, on the other hand, metallic or other powder be submitted to strong compression, the spaces between the fragments become filled with the débris of the crushed particles, and a solid block is the result. Finally, it may be urged that this union of powders of solid metals under the influence of pressure, that is to say, the close approximation of the particles, can be compared to the liquefaction of gases by pressure. At the first view this comparison may appear rash or strained, but it is nothing if we accept the views of Clausius on the nature of gases and liquids. In a gas the molecules are free, but if by pressure at a suitable temperature the molecules are brought within the limits of their mutual attraction, the gas may be liquefied, and under suitable thermal conditions solidified. The mechanical pulverisation of a metal merely detaches groups of molecules from other groups, because the mechanical treatment is imperfect, but the analogy between the solid and a gas has, in a sense, been established; filing has coarsely gasified the mass, but pressure will solidify it as you have already seen.

It is possible that in some of these metallic blocks, the particles are not actually united by the pressure, which may, nevertheless, develop the kind of "mutual attraction" contemplated by Sir W. Thomson as existing between two pieces of matter at distances of less than 10 micro-millimetres.

There are two other properties which solid metals possess, in common with certain fluids, to which I must briefly allude. The first is the power of dissolving gas, which metals in the solid colloid condition possess. I will not offer any experimental illustration on this point, because the work of Graham has been fully dealt with in this theatre by Dr. Odling, and I have, in a course of lectures recently delivered here, shown that just as solid palladium occludes hydrogen, so the alloy of rhodium and lead occludes oxide of nitrogen, which it gives up with explosive violence on heating *in vacuo*, suggesting an analogy with fluid nitro-glycerine. The last property I have to submit to you, is the power which certain solid metals possess of taking up fluids, sometimes with a rapidity which suggests the miscibility of ordinary fluid substances. In reference to this I have found an interesting paper published so long ago as 1713, by the Dutch chemist Homberg,[1] "On Substances which penetrate and which pass through Metals without melting them." He enumerates several substances which will pass through the pores of metals without disturbing the particles, and he points out that mercury penetrates metals without destroying them. Few of us are, I think, familiar with the rapidity with which mercury will pass through tin. Here is a bar, 1 inch wide and ½ inch thick; if a little mercury be rubbed lightly on it the mercury will in 30 seconds penetrate the mass, so that it breaks readily, although before the addition of the mercury, the bar would bend double without any sign of fracture.

With regard to the vaporisation of solid metals, time will only permit me to remind you that Demarçay[2] has shown that *in vacuo* metals evaporate

[1] *Mem. de l'Acad. Royale des Sciences*, 1713 (vol. for 1739, p. 306).
[2] *Comptes Rendus*, vol. xcv., p. 183 (1882).

at much lower temperatures than they do at the ordinary atmospheric pressure, and he suggests that even metals of the platinum group will be found to be volatile at comparatively low temperatures. Merget [1] has shown that the solidification of mercury by extreme cold does not prevent the solid metal evaporating into the atmosphere surrounding it.

With regard to the remaining properties on my list, you will say, surely solids do not show any tendency to diffusion? I have shown [2] that in the case of molten metals the interdiffusion may be extremely rapid, but, with regard to solid metals, some experiments conducted by Sir Frederick Abel prove that carbon can pass from a plate of richly carburised iron to one of iron free from carbon, against which it is tightly pressed. This passage of carbon takes place at the ordinary temperature, and it is difficult to explain the transference of matter without admitting the presence of some action closely allied to the diffusion of liquids.

Finally, can we offer any evidence of surface tension in solid metals? There is only one experiment to submit to you illustrating a point I am still investigating. Some months since Mr. F. W. Fletcher, manager of the works of Messrs. C. Ash & Sons, the well-known dealers in the precious metals, pointed out to me an interesting property of a hard-drawn rod or thick wire of 13-carat gold; the gold being alloyed with silver and copper in the following proportions:—

Gold,	54·17
Copper,	33·33
Silver,	12·53
	100·00

If such a rod be touched with a solution of chloride of iron or certain other soluble chlorides, it will, in a short time, varying from a few seconds to some minutes, break away, the fracture rapidly extending for a distance of some inches.

[The image of the rod was projected on the screen, and in a few seconds after the rod was touched with chloride of iron, it split close to the point of contact with the solution.]

This result may be attended with the absorption of gas, but, in any case, it would appear that in the hard-drawn rod the surface is in a state of tension, which is released by the action of the chloride.

The facts we have considered afford additional evidence as to continuity in the properties of all kinds of matter, and serve as a connecting link with the work of the past, the importance of which is too often overlooked. I trust it will be evident that the analogy of solid metals to fluids has an important bearing on the labours of those who are striving to advance science, to develop art, or to promote the industrial well-being of this country.

[1] *Ann. de Chim. et de Phys.* (4), vol. xxv., p. 121.
[2] *Brit. Assoc. Report*, 1883, p. 402.

SOME CURIOUS PROPERTIES OF METALS AND ALLOYS.

FRIDAY, MAY 11, 1888.

[*An abstract which appeared in the "Proceedings of the Royal Institution,"* 1888, vol xii., p. 267.]

The lecture consisted mainly of experimental demonstrations of the changes induced in metals, either by slight variations in the treatment to which they are subjected to or by rendering them impure by the addition of small quantities of metals or metalloids.

The lecturer began by pointing out that for centuries the early metallurgists investigated the action of exceedingly small quantities of matter upon masses of metal, and he said that, strange as it may seem, the promulgation, in 1803, of Dalton's atomic theory threw a flood of light upon chemical phenomena, but cast into the shade such investigations as those of Bergman which dealt with influences of "traces" upon the masses, and the authority of Berthollet was not sufficient to save them from neglect. In this eventful year of science, 1803, the latter published his essay on chemical statics, in which he stated, as a fundamental proposition, that in comparing the action of bodies on each other, which depends "upon their affinities and mutual proportions, the mass of each has to be considered."[1] His views were successfully contested by Proust, but, as Lothar Meyer says, the influence on chemistry of the rejection of Berthollet's views was remarkable: "All phenomena which could not be attributed to fixed atomic proportions were set aside as not truly chemical, and were neglected. Thus chemists forsook the bridge by which Berthollet had sought to unite the sister sciences, physics and chemistry." Fortunately, however, in this country there was one chemist who had followed up the line of work indicated by the early metallurgists, for in 1803, the same year as that in which both Berthollet's essay and Dalton's atomic theory were published, Charles Hatchett[2] communicated to the Royal Society the results of a research which he had conducted, with the assistance of Cavendish, in order to ascertain "the chemical effects produced on gold by different metallic substances when employed in certain" (often very small) "proportions as alloys."

Allusion was then made to the evidence of the passage of metals into allotropic states, and it was shown that although the importance of the isomeric and allotropic states was abundantly recognised in organic chemistry, it had been much neglected in the case of metals. Special attention was then devoted to the work of Joule and Lyon Playfair, who showed, in 1846, that metals in different allotropic states possessed different atomic volumes, and the lecturer then proceeded to the consideration of the work of Matthiessen who, in 1860, was led to the view that in certain cases when metals were alloyed, they passed into allotropic states, probably the most important generalisation which has as yet been made in connection with the molecular constitution of alloys.

Instances of allotropy in pure metals were then shown to the audience,

[1] English edition (by M. Farrell, M.D.), 1804, p. 5.
[2] *Phil. Trans.*, vol. xciii., p. 43, 1803.

such, for example, as Bolley's lead which oxidises readily in air; Schützenberger's copper; Fritsche's tin, which fell to powder when exposed to an exceptionally cold winter; Gore's antimony; Graham's palladium; and allotropic nickel. It was further shown that metals could be obtained in chemically active states under the following conditions:—Joule proved that when iron is released from its amalgam by distilling away the mercury the metallic iron takes fire on exposure to air, and is, therefore, clearly different from ordinary iron, and is, in fact, an allotropic form of iron. Moissan [1] has shown that similar effects are produced in the case of chromium, manganese, cobalt, and nickel, when released from their amalgams with mercury.

Evidence is not wanting of allotropy in metals released from solid alloys, as well as from fluid amalgams with mercury. Certain alloys may be viewed as solidified solutions, and when such bodies are treated with a suitable solvent, usually an acid, it often happens that one constituent metal is dissolved, and the other released in an insoluble form. Reference was then made to a new alloy of potassium and gold, containing about 10 per cent. of the precious metal. If a fragment of this alloy be thrown upon water, the potassium takes fire, decomposes the water, and the gold is released as a black powder; there is a form of this black or dark-brown gold which appears to be an allotropic modification of gold, as it combines with water to form auric hydride. By heating this dark gold to dull redness, it readily assumes the ordinary golden colour. The Japanese use this gold, released from gold-copper alloys, in a remarkable way, for they produce, by the aid of certain pickling solutions, a beautiful patina on copper which contains only 2 per cent. of gold, while even a trace of the latter metal is sufficient to alter the tint of the patina.

With regard to theoretical views as to molecular change in metals, special care was given to a description of the work of Prof. W. Spring, of Liége, who had furnished much evidence in support of the view that polymerisation of metals, that is the arrangement of atoms in their molecules, could take place even in *solid* alloys of lead and tin.

With reference to the passage of metals into allotropic states under slight external influences, it was stated that Debray [2] has given a case of an alloy in which a simple elevation of temperature induces allotropic change in the constituent metals. It is prepared as follows:—Ninety-five parts of zinc are alloyed by fusion with five parts of rhodium, and the alloy is treated with hydrochloric acid, which dissolves away the bulk of the zinc, leaving a rich rhodium-zinc alloy, containing about 80 per cent. of rhodium. When this alloy is heated in vacuo to a temperature of 400° C., a slight explosion takes place, but no gas is evolved, and the alloy is then insoluble in *aqua regia*, which dissolved it readily before the elevation of temperature caused it to change its state. We are thus presented (as the experiment shown to the audience proved) with another undoubted case of isomerism in alloys, the unstable, soluble modification of the alloy being capable of passing into the insoluble form by a comparatively slight elevation of temperature.

The industrial importance of the passage of metals and alloys into allotropic states, and the possibility of changing the mechanical properties of metals by apparently slight influences, was fully dealt with, and the lecture

[1] *Comptes Rendus*, vol. lxxxviii., p. 180, 1879.
[2] *Ibid.*, vol. xc., p. 1195, 1880.

concluded with a detailed description of the lecturer's own experiments which have since been printed in the *Philosophical Transactions* of the Royal Society, the results showing that very small amounts of metallic impurities exert an extraordinary effect on the tenacity and extensibility of gold, and that small as the amounts of these impurities are, their influence is rigidly controlled by the periodic law of Newlands and Mendeléef, the deleterious action of a metallic impurity being in direct relation to its atomic volume. The audience was asked "to remember that the knowledge of the kind of facts which had been considered comes to us from very early times, for the influence produced on metals by small quantities of added matter had a remarkable effect on the development of chemistry, mainly by sustaining the belief of the early chemists in the possibility of ennobling a base metal so as to transmute it into gold. This was the object to which they devoted life and health, and laboured with fast and vigil. We inherit the results of their labours, and their prayers have been answered in a way they little anticipated, for, from an industrial point of view, if not from a scientific one, metals are 'transmuted' by traces of impurity. Possibly we are nearing an explanation of the causes which are at work, but the fact remains that iron may be changed from a plastic material, which in ornament can be fashioned into the most dainty lines of flow, into one of great endurance, to which, for the present at least, the defence of the country may be trusted, apparently because armour-plates and missiles owe their respective qualities to the fact that carbon, manganese, and chromium have small atomic volumes."

METALS AT HIGH TEMPERATURES.

FRIDAY, FEBRUARY 5, 1892.

Proc. Roy. Inst., vol. xiii., p. 502.

I propose this evening to consider, first, the methods of measuring high temperatures, and, second, to describe certain effects they produce on metals.

Geber, writing in the eighth century, gives directions for obtaining high temperatures, but points to the difficulties that arise in practice, "because fire is not a thing which can be measured, *sed quoniam non est res ignis, quæ mensurari possit.*"[1] It is not sufficient to attain temperatures that are not known to be high; it is necessary, for the purpose of modern investigation, to measure them with accuracy; and few of the early chemists in this country did more in affording a basis for the study of metals at high temperatures than Robert Boyle, the application of whose well-known law to solutions of metals in each other has been made evident by recent work. The 30th December last [1891] was the third centenary of his death; it is well, therefore, that this lecture should begin with a tribute to his memory. He suggested improvements in the ordinary mercurial thermometer,[2] constructed what would appear to be the first air thermometer with an index; and although he did not do much for thermometry at high temperatures, he appears to have been struck by what must have been a quaint device for regulating high temperatures, for he points out that "the great mechanic, Cornelius Drebel[3] made an automatous musical instrument and a furnace which he could regulate to any degree of heat by means of the same instrument." He indicates various degrees of intensity of heat by reference to the colour of a glowing mass of fuel, and says that,[4] "tho' we vulgarly say in English, 'a thing is red hot,' to express a superlative degree of heat, yet, at the forges and furnaces of artificers, by a white heat they understand a further degree of ignition than by a red one." It is not a little strange that for three centuries after his death the same vague expressions have constantly been used in describing high temperatures.

A great step in advance was made in 1701 by Sir Isaac Newton,[5] who applied the law of cooling to the measurement of temperatures beyond the range of the mercurial thermometer, and in the notes which accompany his "Scala graduum caloris" he showed that he knew that the freezing point of lead differs slightly from its melting point.

Eighty years later, Josiah Wedgwood (1782),[6] aided by one of my predecessors, Mr. Alchorne, Assay Master of the Mint, determined a few melting points of metals, and, in communicating a description of his "thermometer for measuring the higher degrees of heat" to the Royal Society, we find him, one thousand years after Geber had said that "fire cannot be measured," still lamenting the want of suitable instruments, saying: "How much it

[1] From the edition of his "Summa Perfectionis Magisterii," p. 28, published in Venice, 1542.

[2] Boyle's Works, Shaw's edition, vol. i., p. 575, 1738.

[3] Cornelius van Drebel, 1572-1634, Boyle, *loc. cit.*, vol. iii., p. 38, 1738.

[4] *Loc. cit.*, vol. ii., p. 28.

[5] *Phil. Trans. Roy. Soc.*, vol. xxii., p. 824.

[6] *Ibid.*, vol. lxxii., p. 305.

is to be wished that the authors (to whom he refers) had been able to convey to us a measure of the heat made use of in their valuable processes; . . . a red heat, a bright red, and a white heat are," Wedgwood adds, "indeterminate expressions, and even though the three stages are sufficiently distinct from each other, they are of too great latitude, and pass into each other by numerous gradations which can neither be expressed in words nor discriminated by the eye." Another ninety years brings us to the last time that the measurements of high temperatures formed the subject of a Friday evening discourse in this Institution. On March 1, 1872, the late Sir William Siemens addressed you on the measurement of "heat by electricity"; [1] and, speaking of the mercurial thermometer, said: "When we ascend the scale of intensity we soon approach a point at which mercury boils, and from that point upwards we are left without a reliable guide, and the result is that we find, in scientific books on chemical processes, statements to the effect that such and such a reaction takes place at a 'dull red,' such another at a 'bright red,' or a 'cherry red,' or a 'white heat'—expressions which remind one," he adds, "of the days of alchemy rather than of chemical science at the present day."

It is not a little singular that the same lament should have been uttered, with so long an interval between, by two prominent technical men, and it suggests that but little experimental work had been done in the meantime with a view to the measurement of high temperatures. This is, however, far from being the case. A vast amount of work was done by physicists and metallurgists whose chief masters were "indefatigable labour, the closest inspection, and hands that were not afraid of the blackness of charcoal"; and their more noteworthy efforts were based on the employment of the air thermometer, in which the expansion of air replaces the expansion of the mercury in the ordinary thermometer, the bulb being of some fire-resisting material.[2] For this purpose, Princep (1827) used a bulb of gold, Pouillet (1836) one of platinum, and Deville and Troost, in a truly splendid series of investigations, adopted bulbs of porcelain, with iodine vapour as the elastic fluid. They ultimately reverted to the use of air.

You will remember that old mercurial thermometers had much information, supposed to be useful, engraven on their scales, and such statements as "water freezes," "water boils," "blood heat," "fever heat," "summer heat," were considered indispensable. It is by exposure to known temperatures that a thermoscope can be converted into a pyrometer for measuring intense heat; and the air or gas thermometer has, in the hands of Deville and Troost, rendered excellent service by enabling such gradations to be effected. The gas thermometer is not, in itself, a handy appliance, for it requires much subsidiary apparatus, and elaborate corrections of various kinds have to be introduced into the numerical data it affords; but it has given many fixed temperatures—such as melting points and boiling points of elements, and of compounds—which may safely be made use of in graduating pyrometers. For very high temperatures, 900° C. and over, we rely on the excellent work of M. Violle [3] on the specific heats of platinum, silver, gold,

[1] *Roy. Inst. Proc.*, vol. vi., p. 438, 1872.

[2] See the excellent bibliography given by C. Barus, "Bull. Geological Survey, U.S.A.," No. 54, 1889.

[3] *Comptes Rendus*, vol. lxxxix., p. 702, 1879; vol. xcii., p. 866, 1881.

palladium, and iridium, which have enabled the melting points of the respective metals to be calculated.

The determinations of temperatures between 300° and 1,000°, which are now generally accepted, also rest upon data accumulated by the aid of the air thermometer, which has thus enabled the graduation to be effected of instruments widely differing from it, that can be trusted to give rapid and accurate indications in daily use. I can only bring before you two of the many kinds which have been devised; they are, however, by far the best that are available, and for the determination of temperatures up to the melting point of platinum, leave little to be desired.

1. A pyrometer which depends on the increase in the resistance of a heated conductor through which a divided electrical current is passing; and

2. One in which the strength of an electric current, generated by the heating of a thermo-junction, is used as a measure of the heat applied to the thermo-junction.

The principle of the electrical resistance pyrometer was indicated by Sir William Siemens ("Collected Papers," vol. ii., "Electricity," p. 84, 1889) in a letter addressed to Dr. Tyndall, dated December, 1860. [Then followed a description of the Siemens pyrometer.]

The Report of a British Association Committee showed, in 1874, that the instrument is liable to changes of zero, but Mr. H. L. Callendar has recently (1887) restored confidence in the method which had been shaken by the Committee. He has proved that if sufficiently pure platinum wire be used, and if the wire be carefully annealed and protected from strain and contamination,[1] resistance pyrometers may be made practically free from changes of zero even when used at temperatures as high as 1,000° C. He attributes the changes of zero to which the Siemens pyrometers are liable to the action on the wire of the clay cylinder on which it is wound, and of the iron tube in which it is enclosed. As the results of his experiments he has introduced certain modifications, which render the instrument not only trustworthy but very sensitive. He winds the platinum wire on a thin plate of mica, and incloses it in a doubly glazed tube of hard porcelain. He uses the zero method of measuring the resistance; but for these and other details of manipulation his own very interesting papers must be consulted. I will only add that I have had the pleasure of working with him in the Mint Laboratory, and I am satisfied that at temperatures about 1,000° the *comparative* results afforded by his method are accurate to the tenth of a degree, a result which would certainly have been deemed impossible a year or two ago.[2]

[1] *Phil. Trans. Roy. Soc.*, vol. clxxviii., 1887, A, pp. 161-233, and vol. clxxxii., 1891, A, pp. 119-157; *Phil. Mag.*, vol. xxxii., July, 1891, p. 104, and vol. xxxiii., Feb. 1892, p. 220.

[2] As this statement has been received with some surprise, it may be as well to state briefly how this degree of accuracy and sensitiveness is attained. The resistance box is compensated for changes of temperature, and changes of resistance in the wires leading to the pyrometer are automatically eliminated. The resistance itself is measured by a modification of the well-known Carey-Foster method. The balancing resistance of the Wheatstone bridge employed, is composed partly of resistance coils and partly of a bridge wire along which a contact key slides. The resistance of a centimetre of this wire is made to correspond to the increase of resistance of the pyrometer produced by a rise of 1° C. The galvanometer can easily be made sensitive to one-hundredth of a centimetre of this bridge wire, so that one-tenth of a centimetre, which corresponds to one-tenth of a degree, can, of course, be measured with certainty.

The necessity for working with small volumes of fused metals, into which the tube of Callendar's pyrometer could not be plunged, has led me to prefer to adopt a method that would be classified under the second heading I have given. A very small thermo-junction may, in fact, be employed in such cases. The use of thermo-junctions for measuring high temperatures appears to have been suggested in 1826 by Becquerel, and adopted by Pouillet in 1836,[1] who advocates the use of iron in conjunction with platinum, but of all the varied combinations of metals and alloys which have been tried from time to time, that proposed by H. Le Chatelier possesses many advantages, on which I have elsewhere dwelt.[2] [Then followed a description of the Le Chatelier pyrometer and the method adopted in calibrating it.]

In leading up to the experiments which follow, in the course of which metals will be exposed to high temperatures, I would remind you that if an ordinary thermometer be plunged into water which is gradually losing its heat to a cold environment, the mercury will fall until the water begins to freeze, but directly this happens the mercury remains stationary until all the water is frozen; so that if the rate of fall be measured with a chronograph, there will be a steady fall to the freezing point of water, then a long arrest, followed by a renewed fall. If these readings be plotted, a well-known time-temperature curve will be obtained. Exactly the same effect is produced when a fluid metal "freezes," and before proceeding further it may be well to determine experimentally the freezing point of gold. [This was shown.]

It will have been evident that the thermo-junction of platinum and platinum-rhodium could not be used for measuring temperatures higher than the melting point of the platinum of which it is made. Metals with higher fusion points than platinum are, however, available; thus iridium will only just melt in the flame produced by the combustion of pure and dry hydrogen and oxygen. By the kindness of Mr. Edward Matthey, a thin rod of iridium has been prepared with much labour, and it can be used as a thermo-junction with a similar rod of iridium alloyed with 10 per cent. of platinum. The junction may be readily melted in the electric arc, and by this means a temperature may be registered which careful laboratory experiments show to be close to 2,000°, and this agrees with the estimate of the melting point of iridium which Violle[3] deduced from calorimetric experiments. [This experiment was shown, a different scale being employed for the screen, as the thermo-electric constants of the iridium, and iridium-platinum couple, are different from those of the platinum and rhodium one previously used.]

It is interesting to remember that within a year, in this Institution, temperatures ranging from $-200°$ to $+2,000°$ have been mapped out, the lower temperature by Prof. Dewar in his memorable Faraday Lecture; the higher point is now measured in public for the first time.

How difficult it is for us to realise what this range of temperature really means! for we have but little power of appreciating temperatures beyond those we can conveniently bear. We, perhaps, know the meaning of extreme

[1] *Comptes Rendus*, vol. iii., 1836, p. 782.

[2] British Association Lecture, *Nature*, vol. xli., 1889, pp. 11-32; *Report Inst. Mech. Eng.*, Oct. 1891, p. 543.

[3] *Comptes Rendus*, vol. lxxxix., 1879, p. 702; vol. xcii., 1881, p. 866.

cold better than great heat, but even the vivid imagery of Dante, who might have been expected to afford some guidance, gives us singularly little help. I think in depicting the terror of torture inflicted by extreme cold he succeeds better than when he describes the suffering of those who are exposed to flames. His words (Canto, xxxiii.)—

> "Blue, pinched, and shrined in ice the spirits stood"—

mark the highest suffering drawn in the "Inferno." It is, however, probable that my failure to appreciate the descriptive powers of Dante may be the result of resentment, for I read with regret that he consigns to the tenth chasm of Hell, not only the coiner who

> "falsified
> The metal with the Baptist's form impressed,"[1]

but also an honest metallurgist, Cappoccio of Sienna, who,

> "by the power
> Of alchemy, . . . aped creative Nature by his subtle art";

and deserved a better fate.

We are now in a position to consider certain other effects of high temperature on metals. Many years ago, my colleague Mr. Lockyer, and I, conducted an investigation on the spectra of the vapours of certain metals[2] at the highest temperatures we could produce, with the aid of the oxyhydrogen flame. We distilled silver, zinc, cadmium, and volatilised iron and other metals, from a lime crucible, and caused their vapours to pass into a horizontal tube of strongly-heated lime. By these experiments we satisfied ourselves that the molecular structure of metals is gradually simplified as higher temperatures are employed; and we came to the conclusion that each molecular simplification is marked by a distinctive spectrum, and that there is also an intimate connection between the facility with which the final stage is reached, the group to which the element belongs, and the place which it occupies in the solar atmosphere. At the highest temperature of the oxyhydrogen flame, molecules of metals are simplified, but their constituent atoms remain unchanged. Mr. Lockyer has, however, since done far more: he has shown that the intense heat of the sun carries the process of molecular simplification much further; and, if we compare the complicated spectra of the vapours of metals produced by the highest temperatures available here with the very simple spectra of the same metals as they exist in the hottest part of the sun's atmosphere, it is difficult to resist the conclusion that the atom of the chemist has itself been changed. My own belief is that these "atoms" are changed, and that iron, as it exists in the sun, is not the vapour of iron as we know it upon earth. We will not dwell in this lecture on the effects of very high temperatures on metals, but rather on the influence of comparatively low temperatures—that is, below whiteness—in changing the number and arrangement of the atoms in metallic molecules. A profound change must occur when the viscous form of sulphur passes spontaneously at the ordinary temperature into the yellow crystalline variety, but the change is accompanied by but little thermal disturbance. In the case of metals there is also abundant evidence that molecular change may

[1] The golden florin of Florence.

[2] *Proc. Roy. Soc.*, vol. xxiii., p. 344, 1875.

take place at low temperatures. Take the fusible alloy of bismuth, lead, and tin, which bears Newton's name, and contains—

Bismuth,	50·00
Lead,	31·25
Tin,	18·75
	100·00

It fuses at 90°; it may be cast round a thermo-junction, and plunged in water and cooled thoroughly until the observer is certain that the mass has returned to the atmospheric temperature; take it out of the water, dry it rapidly, and in a few moments it will become too hot to hold. The "fracture" of the metal is totally different before and after the molecular change which is the cause of this evolution of heat that has taken place. The change, moreover, takes place in the solid metal, and is not due to the release of the latent heat of fusion. The mass, solid as it appears to be, must be the scene of an internal struggle between the molecules in the effort to attain a state of equilibrium, and this conflict is but a type of the action that takes place in many metals and alloys which are of vast industrial importance.

Time will only permit me to deal with three cases of the action of high temperatures on atoms and molecules of metals. In the first case, the arrangement of the atoms in the molecule of a metal, iron, is disturbed, and the result is of great industrial importance. In the second case, the atoms of a metal, gold, appear to combine with those of another metal; and the result, while it is mainly of interest in connection with the history of science, has nevertheless an important bearing upon art. The third case relates to the molecular bombardment which takes place when a small quantity of metal is dissolved in a mass of metallic solvent, and is of interest in connection with modern views both as to osmotic pressure and solution generally.

1. The pyrometric couple is inserted in the centre of a little mass of steel, which is being slowly raised to a bright red heat; when the flame is withdrawn, the spot of light will turn towards the zero end of the scale, falling slowly until a temperature of 655° is reached, and then there will be an abrupt and prolonged arrest. The metal has never been near its melting point, and the evolution of heat must be due to a molecular change in the solid metal. In the case of this particular sample of steel, the evolution of heat is mainly the result of a change in the relation between the carbon and the iron; but by laboratory experiments and careful chronographic records, Osmond has shown that, in the case of certain varieties of steel, it can be demonstrated that what here appears as a single change, attended by an evolution of heat, is really an exceedingly complex one. I have shown that it occurs in the purest iron the chemists can prepare by electrolysis, and I agree with Osmond in believing that the change which occurs in pure iron at 855° is a molecular one, independent of the presence of impurity. If the mass of steel be heated again and allowed to cool, you will observe that the point of "recalescence" appears to be that at which the iron regains its magnetic property;[1] for a magnetised needle is attracted

[1] The temperature at which these molecular changes take place in iron and steel was first demonstrated to an audience in my Newcastle lecture, 1889; but my friend Prof. Reinold, of the Royal Naval College, first arranged an experiment for lecture purposes, which showed the magnetic change simultaneously with the thermal one.

at the moment the arrest of the spot of light on the pyrometer scale marks the temperature at which the change occurs, and at that precise moment a second spot of light, from a mirror mounted on the magnetic needle, will rapidly move away from its zero. I have elsewhere [1] dwelt on the importance of the molecular change in iron and steel, and can now only summarise the significant facts.

[Then followed a short summary of the conditions under which steel is hardened and tempered.]

2. Evidence will now be given in support of the second case it was proposed to treat, and it will be shown that at high temperatures the atoms of metals may truly combine with each other; in fact, taking gold as a basis for the experiments, compounds may be formed which would, had they been known centuries ago, have strangely affected the history of science. When the alchemists subjected the metals to high temperatures, their efforts were mainly directed to the discovery of some substance that would either change base metals to the colour of gold, or would give them the brilliancy of silver. The mediæval chemists believed that there were two distinct substances that would effect this, "one for the white" and another "for the red." Many of their writings might be quoted in support of this view, but a reference to Geber, who wrote in the eighth century, will be sufficient. He pointed out that the transmuting agent "has a tincture of itself so clear and splendid, white or red, clean and incombustible, stable and fixed, that fire cannot prevail against it; . . . and a property of the medicine is to give a splendid colour, white or intensely citrine," to metals to which it is added.

That was the effect expected from the transmuting agent, but do not think that the attempt to produce gold arose entirely from the love of gain. The colour of gold and purple impressed men strangely, and the search for the transmuting agent was most eagerly pursued in times when people lived for art, in a dream of colour. The effort to find the secret of the tint of gold is due to the same impulse which made the French in the thirteenth century manifest a keen "sensitiveness to luminous splendour and intensity of hue," so that, as Sir Frederic Leighton tells us, "a stained glass window, by Cousin, was limpid with hues of amethyst, sapphire, and topaz, and fair as a May morning." The chemists were able to stain glass ruby and purple with gold: why should they not impart the same glories to metals? I could not hope to interest you in what follows, did I not call artists to my aid; and many will remember the glowing words Mr. Ruskin uses,[2] calling purple a "liquid prism and stream of opal," reminding us of the crimson and purple of the poppy, the scarlet and orange of fire and the dawn. No wonder he chides us with turning the lamp of Athena into the safety lamp of the miner, and with getting our purple from coal instead of, as of old, from the murex of the sea; "and thus grotesquely," he says, "we have had forced on us the doubt that held the old world between blackness and fire, and have completed the shadow and the fear of it by giving to a degraded form of modern purple a name from battle—'Magenta.'"

You will remember that Faraday showed that gold, when finely divided, is brilliantly coloured scarlet and purple. Here is a solution of chloride of

[1] Report to the Institution of Mechanical Engineers, *Proceedings*, 1891, p. 543.
[2] "The Queen of the Air," ed. 1887, p. 129; *Times*, Dec. 11, 1891.

gold. Add a little dissolved phosphorus, and the gold is precipitated in an extremely fine state of division, which tinges the solution crimson, but if you try to remove this suspended gold you will only gain a brownish mud. However, any one who possesses a blow-pipe, a bead of gold, and a fragment of one of the most widely diffused metals, aluminium, may stain gold purple through and through.

The series of specimens showed that as the proportion of aluminium is increased, the golden colour of the precious metal is lessened, and when an alloy is formed with about 10 per cent. of aluminium, the fractured surface of the mass is brilliantly white: from this point forwards, as aluminium is added, the tint deepens, until flecks of pink appear, and when 78 parts of gold are added to 22 of aluminium a splendid purple is obtained, in which intensely ruby coloured opaque crystals may readily be recognised. Then, as the quantity of aluminium is still further increased, the alloys lose their colour, and pass to the dull grey hue of the aluminium itself. Perhaps the most remarkable point about the purple alloy is its melting point, which I have shown to be some degrees higher than that of gold itself.[1] There is one other fact of much interest connected with this alloy. When it is treated with dilute hydrochloric acid, chloride of aluminium is formed, and gold is released in a singularly voluminous form. The heat of formation of the gold-aluminium alloy has not been determined, but hydrochloric acid, which will not attack gold, will readily split up this compound, of which more than three-fourths is gold; the compound, in fact, behaves like a distinct metal, having special heats of oxidation and chlorination of its own.

3. Lastly, we come to the question of solutions of metals in each other, One very remarkable instance of the behaviour of metals at high temperatures reveals the fact that the presence of a small amount of metal in a mass of another lowers the freezing point of the mass. In the industrial world this has long been known. Cellini tells us, for instance, that when bronze for his great figure of Perseus, at Florence, was running out of the furnace, it suddenly showed signs of setting, and he, therefore, threw pewter plates and dishes into the ducts through which the metal had to pass—"a thing," he says, "never before done." The fluidity of the metal was immediately increased, and he found every part of the casting "to turn out to admiration."

The excellent work of Heycock and Neville,[2] on the lowering of the freezing points of metals by the addition of other metals should, I would suggest, form the subject of a lecture in this Institution at an early day. I cannot attempt to deal with the matter here. In leading up to these questions of solution, as applied to metals, I would remind you that Lord Rayleigh told us a few evenings since that it was by no means certain that a gas rushing into a vacuous globe ever completely fills it, as there may still be tiny spaces into which "odd molecules" fail to find room to vibrate in. If it is difficult for a gas to entirely fill a vacuous space, you would think it impossible for a small quantity of a metal to rapidly permeate a fluid mass of another metal; nevertheless, so far as analysis can detect, this does happen.

It may be incidentally observed that the relations of the ordinary gases

[1] *Proc. Roy. Soc.*, vol. i., 1891, p. 367.

[2] *Chem. Soc. Journ.*, vol. lv., 1889, p. 666; vol. lvii., 1890, pp. 376, 656; vol. lix., 1891, p. 936; vol. lxi., 1892, p. 888.

to metals are far more intimate than they were formerly supposed to be, and this was proved by Graham's work on the absorption of gases by metals, which has often been dealt with in this Institution. To take only the case of iron, more than twenty years ago Sir Lowthian Bell showed that the relations between carbonic oxide and iron are of singular interest. Ludwig Mond, Quincke, and Langer have since found and isolated most interesting compounds of iron and carbonic oxide.[1] But to return to the solution of metals in metals.

The method of taking autographic curves of the cooling of masses of metal has already been indicated,[2] and they ought to enable much information to be gained as to what is taking place throughout the mass. Such curves should render it possible to ascertain which of the rival theories as to the nature of solution, as applied to salts, is supported by the behaviour of a metal dissolved in a metal. When, for instance, a little aluminium dissolves in gold, is the analogue of a hydride formed, and, if so, is the curve of freezing points of a series of aluminium-gold alloys a continuous one? On the other hand, does the theory advocated by van 't Hoff, Arrhenius, and Ostwald gain support, and do the molecules of the dissolved metals act independently of the solvent—that is, does osmotic pressure come into play? It will be remembered that the law which regulates osmotic pressure has exactly the same form as Boyle's law—that is, the pressure is proportional to the density of the gas or of the solution. Is the view of Arrhenius correct—that, if a solution be very dilute, the molecules of the dissolved substance are dissociated, act independently of each other, and behave like a perfect gas?

It will require years of patient work before these questions can be answered; but it appears certain, from the admirable experiments of Heycock and Neville,[3] to which reference has already been made, that, taking metals with low melting points (such as tin or lead) as solvents, the lowering of the freezing point of the solvent is really due to the bombardment exerted by the molecules of the dissolved metals.

I have extended this investigation by employing as a solvent a mass of fluid gold, which has a high melting point, and is not liable to oxidation, and the results confirm those obtained by Heycock and Neville.

There is yet one other question: When metals are added in small quantities to a metallic mass, may the solvent remain inert? Here is a mass of 1,000 grammes of lead, and to it 15 grammes of gold, or 1·6 atoms for every 100 atoms of lead will now be added. It could be shown that the gold is readily dissolved, and remains dissolved, even if the lead be solidified. Now, to the fluid lead sufficient aluminium will be added to form the purple alloy with the dissolved gold; the mass will be well stirred, but the aluminium will not unite with the lead; it will nevertheless find out the gold, and, after uniting with it, will carry it to the surface of the bath. Thence it can be removed, and the purple colour of the alloy identified, or the gold it contains can be revealed by the method Prof. Hartley[4] has given us for detecting the presence of gold in an alloy by volatilising the alloy in a torrent of sparks from an induction coil, and condensing the vapour on mica.

[1] *Chem. Soc. Journ.*, vol. lix., 1891, pp. 604, 1090.
[2] *Proc. Roy. Soc.*, vol. xlix., 1891, p. 347.
[3] *Loc. cit.*
[4] *Proc. Roy. Soc.*, vol. xlvi., 1889, p. 88.

The union of the aluminium and the gold must, however, be peculiar. Crookes [1] has shown that when this alloy is used as an electrode in a vacuum tube, the gold is volatilised from the alloy and deposited as a film on the glass, leaving the aluminium behind.

The purple alloy presents us with the most interesting case yet known of a molecule built up of purely metallic atoms, but we are certain that the atoms are still those of gold and aluminium—that is, the atoms of the united metals remain unchanged. The interest in this substance is deepened if it be remembered that our aim at the present day is the same as that of the alchemists, for we are striving, as they did, to attack and change the chemists' atoms themselves. We seek, as truly as they, to effect the transmutations, which, as Boyle said, would "be none the less real for not being gainful," and employ high temperatures in the hope of simplifying the molecular structure of metals. We no longer consider gold to be the "sum of perfection," but still retain the belief expressed by Geber, eleven hundred years ago, that, "if we would change metals, we must needs use excess of heat." A poet also appears to have felt this, for George Herbert writes in the seventeenth century—

> "I know . . . what the stars conspire,
> What willing Nature speaks, what forced by fire";

thus comparing the ordinary response of nature to the investigator, with the evidence he elicits from her by heat.

By fusing gold, and staining it "the purple of the dawn," a new interest has been given to the metal which the alchemists always connected with the sun; and for further proof that metallic atoms may be changed, we must turn to the sun itself, as to the great metallurgical centre, where "all the elements shall melt with fervent heat."

[1] *Ibid.*, vol. l., 1891, p. 88.

THE RARER METALS AND THEIR ALLOYS.[1]

FRIDAY, MARCH 15, 1895.

[*Proc. Roy. Inst.*, vol. xiv., p. 497.]

"For reason is not the only attribute of man, nor is it the only faculty which he habitually employs for the ascertainment of truth."—*G. J. Romanes.*

The study of metals possesses an irresistible charm for us, quite apart from its vast national importance. How many of us made our first scientific experiment by watching the melting of lead, little thinking that we should hardly have done a bad life's work if the experiment had been our last, provided we had only understood its full significance. How few of us forget that we wistfully observed at an early age the melting in an ordinary fire of some metallic toy of our childhood; and such an experiment has, like the "Flat iron for a farthing," in Mrs. Ewing's charming story, taken a prominent place in literature which claims to be written for children. Hans Andersen's fairy tale, for instance, the "History of a Tin Soldier," has been read by children of all ages and of most nations. The romantic incidents of the soldier's eventful career need not be dwelt upon; but I may remind you that at its end he perished in the flames of an ordinary fire, and all that could subsequently be found of him was a small heart-shaped mass. There is no reason to doubt the perfect accuracy of the story recorded by Andersen, who at least knew the facts, though his statement is made in popular language. No analysis is given of the tin soldier; in a fairy tale it would have been out of place, but the latest stage of his evolution is described, and the record is sufficient to enable us to form the opinion that he was composed of both tin and lead, certain alloys of which metals will burn to ashes like tinder. His uniform was doubtless richly ornamented with gold lace. Some small amount of one of the rarer metals had probably—for on this point the history is silent—found its way into his constitution, and by uniting with the gold, formed the heart-shaped mass which the fire would not melt, as its temperature could not have exceeded 1,000° C.: for we are told that the golden rose, worn by the *artiste* who shared the soldier's fate, was also found unmelted. The main point is, however, that the presence of one of the rarer metals must have endured the soldier with his singular endurance, and in the end left an incorruptible record of him.

This incident has been taken as the starting point of the lecture, because we shall see that the ordinary metals so often owe remarkable qualities to the presence of a rarer metal which fits them for special work.

This early love of metals is implanted in us as part of our "unsquandered heritage of sentiments and ideals which has come down to us from other ages," but future generations of children will know far more than we did; for the attempt will be made to teach them that even psychology is a branch of molecular physics, and they will, therefore, see far more in the melted toy than a shapeless mass of tin and lead. It is really not an inert thing; for some time after it was newly cast, it was the scene of intense molecular

[1] From *Nature*, May 2 and 9, 1895.

activity. It probably is never molecularly quiescent, and a slight elevation of temperature will excite in it rapid atomic movement anew. The nature of such movement I have indicated on previous occasions when, as now, I have tried to interest you in certain properties of metals and alloys.

This evening I appeal incidentally to higher feelings than interest, by bringing before you certain phases in the life-history of metals which may lead you to a generous appreciation of the many excellent qualities they possess.

Metals have been sadly misunderstood. In the belief that animate beings are more interesting, experimenters have neglected metals, while no form of matter in which life can be recognised is thought to be too humble to receive encouragement. Thus it is that bacteria, with repulsive attributes and criminal instincts, are petted and watched with solicitude, and comprehensive schemes are submitted to the Royal Society for their development, culture, and even for their "education," [1] which may, it is true, ultimately make them useful metallurgical agents, as certain micro-organisms have already proved their ability to produce arseniuretted hydrogen from oxide of arsenic.[2]

It will not be difficult to show that the methods which have proved so fruitful in results when applied to the study of living things, are singularly applicable to metals and alloys, which really present close analogies to living organisms. This must be a new view to many and it may be said, "it is well known that uneducated races tend to personify or animate external nature," and it is strange, therefore, to attempt, before a cultured audience, to trace analogies which must appear to be remote, between moving organisms and inert alloys, but "the greater the number of attributes that attach to anything, the more real that thing is." [3] Many of the less known metals are very real to me, and I want them to be so to you; listen to me, then, as speaking for my silent metallic friends, while I try to secure for them your sympathy and esteem.

First, as regards their origin and early history. I fully share Mr. Lockyer's belief as to their origin, and think that a future generation will speak of the evolution of metals as we now do of that of animals, and that observers will naturally turn to the sun as the field in which this evolution can best be studied.

To the alchemists metals were almost sentient; they treated them as if they were living beings, and had an elaborate pharmacopœia of "medicines" which they freely administered to metals in the hope of perfecting their constitution. If the alchemists constantly drew parallels between living things and metals, it is not because they were ignorant, but because they recognised in metals the possession of attributes which closely resemble those of organisms. "The first alchemists were gnostics, and the old beliefs of Egypt blended with those of Chaldea in the second and third centuries. The old metals of the Egyptians represented men, and this is probably the origin of the *homunculus* of the middle ages, the notion of the creative power of metals and that of life being confounded in the same symbol." [4]

[1] Dr. Percy Frankland specially refers to the "education" of bacilli for adapting them to altered conditions. *Roy. Soc. Proc.*, vol. lvi., 1894, p. 539.

[2] Dr. Brauner. *Chem. News*, Feb. 15, 1895, p. 79.

[3] Lotze, "Metaphysic," sec. 49, quoted by Illingworth. "Personality, Human and Divine." Bampton Lectures, 1894, p. 43.

[4] Berthelot, *Les origines de l'alchimie*, 1885, p. 60.

Thus Albertus Magnus traces the influence of congenital defects in the generation of metals and of animals, and Basil Valentine symbolises the loss of metalline character, which we now know is due to oxidation, to the escape from the metal of an indestructible spirit which flies away and becomes a soul. On the other hand, the "reduction" of metals from their oxides was supposed to give the metals a new existence. A poem [1] of the thirteenth century well embodies this belief in the analogies between men and metals, in the quaint lines:—

> "Homs ont l'estre comme metaulx,
> Vie et augment des vegetaulx,
> Instinct et sens comme les bruts,
> Esprit comme ange en attributs."

"Men have being"—constitution—like metals; you see how closely metals and life were connected in the minds of the alchemists, and we inherit their traditions.

"Who said these old renowns, dead long ago, could make me forget the living world?" are words which Browning places in the lips of Paracelsus, and we metallurgists are not likely to forget the living world; we borrow its definitions, and apply them to our metals. Thus nobility in metals as in men, means freedom from liability to tarnish, and we know that the rarer metals are like rarer virtues, and have singular power in enduring their more ordinary associates with firmness, elasticity, strength, and endurance. On the other hand, some of the less known metals appear to be mere "things" which do not exist for themselves, but only for the sake of other metals to which they can be united. This may, however, only seem to be the case because we as yet know so little about them. The question naturally arises, how can the analogies between organic and inorganic bodies now be traced. I agree with my colleague at the Ecole des Mines of Paris, Prof. Urbain Le Verrier, in thinking that it is possible [2] to study the biology, the anatomy, and even the pathology of metals.

The anatomy of metals—that is, their structure and framework—is best examined by the aid of the microscope, but if we wish to study the biology and pathology of metals, the method of autographic pyrometry, which I brought before you in a Friday evening lecture delivered in 1892, will render admirable service, for, just as in biological and pathological phenomena vital functions and changes of tissue are accompanied by a rise or fall in temperature, so molecular changes in metals are attended with an evolution or absorption of heat. With the aid of the recording pyrometer we now "take the temperature" of a mass of metal or alloy in which molecular disturbance is suspected to lurk, as surely as a doctor does of a patient in whom febrile symptoms are manifest.

It has, moreover, long been known that we can submit a metal or an alloy in its normal state to severe stress, record its power of endurance, and then, by allowing it to recover from fatigue, enable it to regain some, at least, of its original strength. The human analogies of metals are really

[1] *Ler Remonstrances ou la complainte de nature a l'alchymiste errant.* Attributed to Jehan de Meung, who with Guillaume de Lorris wrote the *Roman de la Rose.* M. Méon, the editor of the edition of 1814 of this celebrated work, doubts, however, whether the attribution of the *complainte de nature* to Meung is correct.

[2] "La Métallurgie en France," 1894, p. 2.

very close indeed, for, as is the case with our own mental efforts, the internal molecular work which is done in metals often strengthens and invigorates them. Certain metals have a double existence, and, according to circumstances, their behaviour may be absolutely harmful or entirely beneficial. The dualism we so often recognise in human life becomes allotropism in metals, and they, strangely enough, seem to be restricted to a single form of existence if they are absolutely free from contamination, for probably an absolutely pure metal cannot pass from a normal to an allotropic state. Last, it may be claimed that some metals possess attributes which are closely allied to moral qualities, for, in their relations with other elements, they often display an amount of discrimination and restraint that would do credit to sentient beings.

Close as this resemblance is, I am far from attributing consciousness to metals, as their atomic changes result from the action of external agents, while the conduct of conscious beings is not determined from without, but from within. I have, however, ventured to offer the introduction of this lecture in its present form, because any facts which lead us to reflect on the unity of plan in nature, will aid the recognition of the complexity of atomic motion in metals upon which it is needful to insist.

The foregoing remarks have special significance in relation to the influence exerted by the rarer metals on the ordinary ones. With the exception of the action of carbon upon iron, probably nothing is more remarkable than the action of the rare metals on those which are more common; but their peculiar influence often involves, as we shall see, the presence of carbon in the alloy.

Which, then, are the rarer metals, and how may they be isolated? The chemist differs somewhat from the metallurgist as to the application of the word "rare." The chemist thinks of the "rarity" of a compound of a metal; the metallurgist, rather of the difficulty of isolating the metal from the state of combination in which it occurs in nature.

The chemist in speaking of the reactions of salts of the rarer metals, in view of the wide distribution of limestone and pyrolusite, would hardly think of either calcium or manganese as being among the rarer metals. The metallurgist would consider pure calcium or pure manganese to be very rare. I have only recently seen comparatively pure specimens of the latter.

The metals which, for the purposes of this lecture, may be included among the rarer metals are: (1) those of the platinum group, which occur in nature in the metallic state; and (2) certain metals which in nature are usually found as oxides or in an oxidised form of some kind, and these are chromium, manganese, vanadium, tungsten, titanium, zirconium, uranium, molybdenum (which occurs, however, as sulphide). Incidental reference will be made to nickel and cobalt.

Of the rare metals of the platinum group I propose to say but little; we are indebted for a magnificent display of them in the library to my friends Messrs. George and Edward Matthey and to Mr. Sellon, all members of a great firm of metallurgists. You should specially look at the splendid mass of palladium, extracted from native gold of the value of £2,500,000, at the melted and rolled iridium, and at the masses of osmium and rhodium. No other nation in the world could show such specimens as these, and we are justly proud of them.

These metals are so interesting and precious in themselves, that I hope you will not think I am taking a sordid view of them by saying that the contents of the case exhibited in the library are certainly not worth less than ten thousand pounds.

As regards the rarer metals which are associated with oxygen, the problem is to remove the oxygen, and this is usually effected either by affording the oxygen an opportunity for uniting with another metal, or by reducing the oxide of the rare metal by carbon, aided by the tearing effect of an electric current. [An electric furnace was exhibited, in which metallic chromium was reduced.]

The use of alkaline metals in separating oxygen from other metals is well known. I cannot enter into its history here, beyond saying that if I were to do so, frequent references to the honoured names of Berzelius, Wöhler, and Winkler would be demanded.[1]

Mr. Vautin has recently shown that granulated aluminium may readily be prepared, and that it renders great service when employed as a reducing agent. He has lent me many specimens of rarer metals which have been reduced to the metallic state by the aid of this finely-granulated aluminium; and I am indebted to his assistant, Mr. Picard, who was lately one of my own students at the Royal School of Mines, for aid in the preparation of certain other specimens which have been isolated in my laboratory at the Mint.

The experiment you have just seen enables me to justify a statement I made respecting the discriminating action which certain metals appear to exert. The relation of aluminium to other metals is very singular. When, for instance, a small quantity of aluminium is present in cast iron, it protects the silicon, manganese, and carbon from oxidation.[2] The presence of silicon in aluminium greatly adds to the brilliancy with which aluminium itself oxidises and burns.[3] It is also asserted that aluminium, even in small quantity, exerts a powerful protective action against the oxidation of the silver-zinc alloy which is the result of the desilverisation of lead by zinc.

Moreover, heat aluminium in mass to redness in air, where oxygen may be had freely, and a film of oxide which is formed will protect the mass from further oxidation. On the other hand, if finely divided aluminium finds itself in the presence of an oxide of a rare metal, at an elevated temperature, it at once acts with energy and promptitude, and releases the rare metal from the bondage of oxidation. I trust, therefore, you will consider my claim that a metal may possess moral attributes has been justified. Aluminium, moreover, retains the oxygen it has acquired with great fidelity, and will only part with it again at very high temperatures, under the influence of the electric arc in the presence of carbon.

[A suitable mixture of red lead and aluminium was placed in a small crucible heated in a wind furnace, and in two minutes an explosion announced the termination of the experiment. The crucible was shattered to fragments.]

The aluminium loudly protests, as it were, against being entrusted with

[1] An interesting paper, by H. F. Keller, on the reduction of oxides of metals by other metals, will be found in the *Journal of the American Chemical Society*, Dec. 1894, p. 833.

[2] *Bull. Soc. Chim.*, Paris, vol. xi., 1894, p. 377.

[3] Ditte, "Leçons sur les Métaux," part ii., 1891, p. 206.

such an easy task, as the heat engendered by its oxidation had not to be used in melting a difficultly fusible metal like chromium, the melting point of which is higher than that of platinum.

It is admitted that a metal will abstract oxygen from another metal as the reaction is more exothermic than that by which the oxide to be decomposed, was originally formed. The heat of formation of alumina is 391 calories, and that of oxide of lead is 51 calories; so that it might be expected that metallic aluminium, at an elevated temperature, would readily reduce oxide of lead to the metallic state.

The last experiment, however, proved that the reduction of oxide of lead by aluminium is effected with explosive violence, the temperature engendered by the reduction being sufficiently high to volatilise the lead. Experiments of my own show that the explosion takes place with much disruptive power when aluminium reacts on oxide of lead *in vacuo*, and that if coarsely ground, fused litharge be substituted for red lead, the action is only accompanied by a rushing sound. The result is, therefore, much influenced by the rapidity with which the reaction can be transmitted throughout the mass. It is this kind of experiment which makes us turn with such vivid interest to the teaching of the school of St. Claire Deville, the members of which have rendered such splendid services to physics and metallurgy. They do not advocate the employment of the mechanism of molecules and atoms in dealing with chemical problems, but would simply accumulate evidence as to the physical circumstances under which chemical combination and dissociation take place, viewing these as belonging to the same class of phenomena as solidification, fusion, condensation, and evaporation. They do not even insist upon the view that matter is minutely granular, but in all cases of change of state, make calculations on the basis of work done, viewing changed "internal energy" as a quantity which should reappear when the system returns to the initial state.

A verse, of some historical interest, may appeal to them. It occurs in an old poem to which I have already referred as being connected with the *Roman de la Rose*, and it expresses nature's protest against those who attempt to imitate her works by the use of mechanical methods. The "argument" runs thus:—

> "Comme Nature se complaint,
> Et dit sa douleur et son plaint
> A ung sot souffleur sophistique
> Qui n'use que d'art méchanique."

If the "use of mechanical art" includes the study of chemistry on the basis of the mechanics of the atoms, I may be permitted to offer the modern school the following rendering of nature's plaint:—

> How nature sighs without restraint,
> And grieving makes her sad complaint
> Against the subtle sophistry
> Which trusts atomic theory.

An explosion such as is produced when aluminium and oxide of lead are heated in the presence of each other, which suggested the reference to the old French verse, does not often occur, as in most cases the reduction of the rarer metals by aluminium is effected quietly.

Zirconium is a metal which may be so reduced. I have in this way prepared small quantities of zirconium from its oxide, and have formed a greenish alloy of extraordinary strength by the addition of $\frac{2}{10}$ per cent. of it to gold, and there are many circumstances which lead to the belief that the future of zirconium will be brilliant and useful. I have reduced vanadium and uranium from their oxides by means of aluminium as well as manganese, which is easy, and titanium, which is more difficult. Tungsten, in fine specimens, is also before you, and allusion will be made subsequently to the uses of these metals. At present I would draw your attention to some properties of titanium which are of special interest. It burns with brilliant sparks in air; and as few of us have seen titanium burn, it may be well to burn a little in this flame. [Experiment performed.] Titanium appears to be, from the recent experiments of M. Moissan, the most difficultly fusible metal known; but it has the singular property of burning in nitrogen—it presents, in fact, the only known instance of vivid combustion in nitrogen.[1]

Titanium may be readily reduced from its oxide by the aid of aluminium. Here are considerable masses, sufficiently pure for many purposes, which I have recently prepared in view of this lecture.

The other method by which the rarer metals may be isolated is that which involves the use of the electrical furnace. In this connection the name of Sir William Siemens should not be forgotten. He described the use of the electric arc-furnace in which the carbons were arranged vertically, the lower carbon being replaced by a carbon crucible, and in 1882 he melted in such a furnace no less than ten pounds of platinum during an experiment at which I had the good fortune to assist. It may fairly be claimed that the large furnaces with a vertical carbon in which aluminium and other metals are now reduced by the combined electrolytic action and tearing temperature of the arc, are the direct outcome of the work of Siemens.

In the development of the use of the electric arc for the isolation of the rare, difficultly fusible, metals Moissan stands in the front rank. He points out[2] that Despretz[3] used in 1849, the heat produced by the arc of a powerful pile; but Moissan was the first to employ the arc in such a way as to separate its heating effect from the electrolytic action it exerts. This he does by placing the poles in a horizontal position, and by reflecting their heat into a receptacle below them. He has shown, in a series of classical researches, that employing 800 amperes and 110 volts a temperature of at least 3,500° may be attained, and that many metallic oxides which until recently were supposed to be irreducible may be readily made to yield the metal they contain.[4]

A support or base for the metal to be reduced is needed, and this is afforded by magnesia, which appears to be absolutely stable at the utmost

[1] Lord Rayleigh has since stated that titanium does not combine with argon; and M. Guntz points out that lithium in combining with nitrogen produces incandescence. M. Moissan has also shown that uranium does not absorb argon.

[2] *Ann. de Chim. et de Phys.*, vol. iv., 1895, p. 365.

[3] *Comptes Rendus*, vol. xxviii., p. 755, and vol. xxix., 1849, pp. 48, 545, 712.

[4] The principal memoirs of M. Moissan will be found in the *Comptes Rendus*, vol. cxv., 1892, p. 1031; *ibid.*, vol. cxvi., 1893, pp. 347, 349, 549, 1222, 1225, 1429; *ibid.*, vol. cxix., 1894, pp. 15, 20, 935; *ibid.*, vol. cxx., 1895, p. 290. The more important of the metals he has isolated are uranium, chromium, manganese, zirconium, molybdenum tungsten, vanadium, and titanium. There is an important paper by him on the various forms of the electric furnace in the *Ann. de Chim. et de Phys.*, vol. iv., 1895, p. 365.

temperatures of the arc. An atmosphere of hydrogen may be employed to avoid oxidation of the reduced metal, which, if it is not a volatile one, remains at the bottom of the crucible almost always associated with carbon—forming, in fact, a carbide of the metal. I want to show you the way in which the electric furnace is used, but unfortunately the reductions are usually very tedious, and it would be impossible to actually show you much if I were to attempt to reduce before you any of the rarer metals; but as the main object is to show you how the furnace is used, it may be well to *boil* some silver at a temperature of some 2,500°, and subsequently to melt chromium in the furnace (Fig. 4). This furnace consists of a clay receptacle, A, lined with magnesia, B. A current of 60 amperes and 100 volts is introduced by the carbon poles C, C′; an electro-magnet, M, is provided to deflect the arc on to the metal to be melted. [By means of a lens and mirror, D, E, the image of the arc and of the molten metal was projected on to a screen.

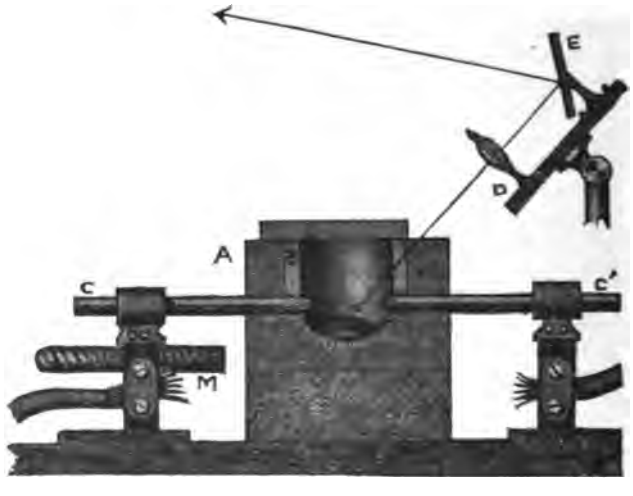


Fig. 4.

For this purpose it was found convenient to make the furnace much deeper than would ordinarily be the case.]

It may be well to state briefly what is seen when the furnace is arranged for the melting of metallic chromium. Directly the current is passed, the picture reflected by the mirror shows the interior of the furnace as a dark crater, the dull red poles revealing the metallic lustre and grey shadows of the metal beneath them. A little later these poles become tipped with dazzling white, and, in the course of a few minutes, the temperature rises to about 2,500° C. Such a temperature will keep chromium well melted, though a thousand degrees more may readily be attained in a furnace of this kind. Each pole is soon surrounded with a lambent halo of the green-blue hue of the sunset, the central band of the arc changing rapidly from peach-blossom to lavender and purple. The arc can then be lengthened, and as the poles are drawn further and further asunder, the irregular masses of chromium fuse in silver droplets, below an intense blue field of light, passing

into green and lustrous emerald; then the last fragments of chromium melt into a shining lake, which reflects the glowing poles in a glory of green and gold, shot with orange hues. Still a few minutes later, as the chromium burns, a shower of brilliant sparks of metal are projected from the furnace amid the clouds of russet or brown vapours which wreath the little crater; whilst if the current is broken, and the light dies out, you wish that Turner had painted the limpid tints, and that Ruskin might describe their loveliness.

The effect when either tungsten or silver replaces chromium is much the same, but, in the latter case, the glowing lake is more brilliant in its turbulent boiling, and blue vapours rise to be condensed in the iridescent beads of distilled silver which stud the crater walls.

Such experiments will probably lend a new interest to the use of the arc in connection with astronomical metallurgy, for, as George Herbert said long ago—

> "Stars have their storms even in a high degree,
> As well as we;"

and Lockyer has shown how important it is, in relation to such storms, to be able to study the disturbances in the various strata of the stellar or solar atmosphere. Layers of metallic vapour which differ widely in temperature can be more readily obtained by the use of the electrical furnace than when a fragment of metal is melted and volatilised by placing it in the arc, on the lower carbon.

It must not be forgotten that the use of the electric arc between carbon poles renders it practically impossible to prepare the rare metals without associating them with carbon, often forming true carbides; but it is possible in many cases to separate the carbon by subsequent treatment. Moissan has, however, opened up a vast field of industrial work by placing at our disposal practically all the rarer infusible metals which may be reduced from oxides, and it is necessary for us now to consider how we may best enter upon our inheritance. Those members of the group which we have known long enough to appreciate are chromium and manganese, and these we have only known free from carbon for a few months. In their carburised state they have done excellent service in connection with the metallurgy of steel; and may we not hope that vanadium, molybdenum, titanium, and uranium will render still greater services? My object in this lecture is mainly to introduce you to these metals, which hitherto few of us have ever seen except as minute cabinet specimens, and we are greatly indebted to M. Moissan for sending us beautiful specimens of chromium, vanadium, uranium, zirconium, tungsten, molybdenum, and titanium. [These were exhibited.]

The question naturally arises: Why is the future of their usefulness so promising? Why are they likely to render better service than the common metals with which we have long been familiar? It must be confessed that as yet we know but little what services these metals will render when they stand alone; we have yet to obtain them in a state of purity, and have yet to study their properties, but when small quantities of any of them are associated or alloyed with other metals, there is good reason to believe that they will exert a very powerful influence. In order to explain this, I must appeal to the physical method of inquiry to which I have already referred.

It is easy to test the strength of a metal or of an alloy; it is also easy to determine its electrical resistance. If the mass stands these tests well, its suitability for certain purposes is assured; but a subtle method of investigation has been afforded by the results of a research entrusted to me by a committee of the Institution of Mechanical Engineers, over which Dr. Anderson, of Woolwich, presides. We can now gather much information as to the way in which a mass of metal has arranged itself during the cooling from a molten condition, which is the necessary step in fashioning it into a useful form; it is possible to gain insight into the way in which a molten mass of a metal or an alloy, molecularly settles itself down to its work, so to speak, and we can form conclusions as to its probable sphere of usefulness.

The method is a graphic one, such as this audience is familiar with, for Prof. Victor Horsley has shown in a masterly way that traces on smoked paper may form the record of the heart's action under the disturbing influence caused by the intrusion of a bullet into the human body. I hope to show you by similar records the effect, which though disturbing is often far from prejudicial, of the introduction of a small quantity of a foreign element into the "system" of a metal, and to justify a statement which I made earlier, as to the applicability of physiological methods of investigation to the study of metals. [A description was then given of pyrometric work and a number of curves were shown representing autographic records of the cooling of typical metals and alloys.]

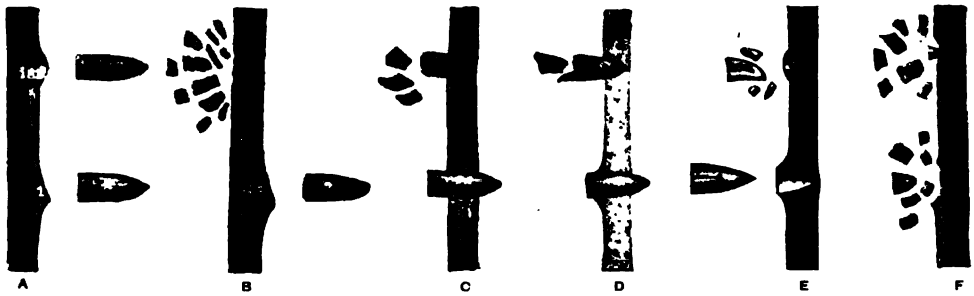
It may be well to point to a few instances in which the industrial use of such of the rarer metals, as have been available in sufficient quantity, is made evident. Modern developments in armour-plate and projectiles will occur to many of us at once. This diagram (Fig. 5) affords a rapid view of the progress which has been made, and in collecting the materials for it from various sources, I have been aided by Mr. Jenkins. The effect of projectiles of approximately the same weight, when fired with the same velocity against 6-inch plates, enables comparative results to be studied, and illustrates the fact that the rivalry between artillerists who design guns, and metallurgists who attempt to produce both impenetrable armour-plates and irresistible projectiles, forms one of the most interesting pages in our national history. When metallic armour was first applied to the sides of war vessels, it was of wrought iron, and proved to be of very great service by absolutely preventing the passage of ordinary cast-iron shot into the interior of the vessel, as was demonstrated during the American Civil War in 1866. It was found to be necessary, in order to pierce the plates, to employ harder and larger projectiles than those then in use, and the chilled cast-iron shot with which Colonel Palliser's name is identified proved to be formidable and effective. The point of such a projectile was sufficiently hard to retain its form under impact with the plate, and it was only necessary to impart a moderate velocity to a shot to enable it to pass through the wrought-iron armour (A, Fig. 5).

It soon became evident that in order to resist the attack of such projectiles with a plate of any reasonable thickness, it would be necessary to make the plate harder, so that the point of the projectile should be damaged at the moment of first contact, and the reaction to the blow distributed over a considerable area of the plate. This object could be attained by either using a steel plate in a more or less hardened condition, or by employing

a plate with a very hard face of steel, and a less hard but tougher back. The authorities in this country during the decade, 1880-90, had a very high opinion of plates that resisted attack without the development of through-cracks, and this led to the production of the compound plate. The backs of these plates (B, Fig. 5) are of wrought iron, the fronts are of a more or less hard variety of steel, either cast on, or welded on by a layer of steel of an intermediate quality cast between the two plates. Armour-plates of this kind differ in detail, but the principle of their construction is now generally accepted as correct.

Such plates, shown by Plate B, resisted the attack of large Palliser shells admirably, as when such shells struck the plate they were damaged at their points, and the remainder of the shell was unable to perforate the armour against which it was directed. An increase in the size of the projectiles led, however, to a decrease in the resisting power of the plates, portions of the hard face of which would at times be detached in flakes from the junction of the steel and the iron. An increase in the toughness of the

ATTACK OF 6-INCH ARMOUR-PLATES BY 4·72-INCH SHELLS, WEIGHING 57·2 LBS.



A	B	C	D	E	F
Wrought iron. 1888.	Compound plate. 1888.	Steel. 1888.	Steel. 1894.	Nickel-steel. 1894.	Harveyed nickel-steel. 1894.

Fig. 5.—The upper series of projectiles are Palliser chilled-iron shells, and the lower are chrome-steel. In each case the velocity of the projectile is approximately 1,640 foot-seconds, and the energy 1,070 foot-tons.

projectiles by a substitution of forged chrome-steel for chilled iron (see lower part of Plate B) secured a victory for the shot, which was then enabled to impart its energy to the plate faster than the surface of the plate itself could transmit the energy to the back. The result was that the plate was overcome, as it were, piecemeal; the steel surface was not sufficient to resist the blow itself, and was shattered, leaving the projectile an easy victory over the soft back. The lower part of Plate, B (in Fig. 5), represents a similar plate to that used in the "Nettle" trials of 1888.[1] It must not be forgotten in this connection, that the armour of a ship is but little likely to be struck twice by heavy projectiles in the same place, although it might be by smaller ones.

Plates made entirely of steel, on the other hand, were found, prior to

[1] *Proc. Inst. Civ. Eng.*, 1889, vol. xcviii., p. 1, *et seq.*

1888, to have a considerable tendency to break up completely when struck by the shot. It was not possible, on that account, to make their faces as hard as those of compound plates; but while they did not resist the Palliser shot nearly so well as the rival compound plate, they offered more effective resistance to steel shot (see lower part of plate C, Fig. 5).

It appears that Berthier recognised, in 1820, the great value of chromium when alloyed with iron; but its use for projectiles, although now general, is of comparatively recent date, and these projectiles now commonly contain from 1·2 to 1·5 per cent. of chromium, and will hold together even when they strike steel plates at a velocity of 2,000 feet per second [1] (see lower part of plate D); and unless the armour-plate is of considerable thickness, such projectiles will even carry bursting charges of explosives through it. [The behaviour of a chromium-steel shell, made by Mr. Hadfield, was dwelt upon, and the shell was exhibited.]

It now remained to be seen what could be done in the way of toughening and hardening the plates so as to resist the chrome-steel shot. About the year 1888, very great improvements were made in the production of steel plates. Devices for hardening and tempering plates were ultimately obtained, so that the latter were hard enough throughout their substance to give them the necessary resisting power without such serious cracking as had occurred in previous ones. But in 1889, Mr. Riley exhibited, at the meeting of the Iron and Steel Institute, a thin plate that owed its remarkable toughness to the presence of nickel in the steel. The immediate result of this was the plates could be made to contain more carbon, and hence be harder, without at the same time having increased brittleness; such plates, indeed, could be water hardened and yet not crack.

The plate E (Fig. 5) represents the behaviour of nickel-steel armour. It will be seen that it is penetrated to a much less extent than in the former case; at the same time there is entire absence of cracking.

Now as to the hardening processes. Evrard had developed the use of the lead bath in France, while Captain Tressider [2] had perfected the use of the water-jet in England for the purpose of rapidly cooling the heated plates. The principle adopted in the design of the compound plates has been again utilised by Harvey, who places the soft steel or nickel-steel plate in a furnace of suitable construction, and covers it with carbonaceous material such as charcoal, and strongly heats it for a period, which may be as long as 120 hours. This is the old Sheffield process of cementation, and the result is to increase the carbon from 0·35 per cent. in the body of the plate to 0·6 per cent., or even more at the front surface, the increase in the amount of carbon only extending to a depth of 2 or 3 inches in the thickest armour.

The carburised face is then "chill-hardened," the result being that the best chrome-steel shot are shattered at the moment of impact, unless they are of very large size as compared with the thickness of the plate. The interesting result was observed lately [3] of shot doing less harm to the plate, and penetrating less, when its velocity was increased beyond a certain value, a result due to a superiority in the power of the face of the plate to transmit energy over that possessed by the projectile, which was itself damaged,

[1] *Journal U.S. Artillery*, 1893, vol. ii., p. 497.
[2] Weaver, "Notes on Armour," *Journal of the U.S. Artillery*, vol. iii., 1894, p. 417.
[3] Brassey's *Naval Annual*, 1894, p. 367.

when a certain rate was exceeded. At a comparatively low velocity the point of the shot would resist fracture, but the energy of the projectile is not then sufficient to perforate the plate, which would need the attack of a much larger gun firing a projectile at a lower velocity.

The tendency to-day is to dispense with nickel, and to use ordinary steel, "Harveyed"; [1] this gives excellent 6-inch plates, but there is some difference of opinion as to whether it is advantageous to omit nickel in the case of very thick plates, and the problem is now being worked out by the method of trial. Probably, too, the Harveyed plates will be much improved by judicious forging after the process, as is indicated by some recent work done in America. The use of chromium in the plates may lead to interesting results.

Turn for a moment to the *Majestic* class of ships, the construction of which we owe to the genius of Sir William White, to whom I am indebted for a section representing the exact size of the protection afforded to the barbette of the *Majestic*. [This section was exhibited.] Her armour is of the Harveyed steel, which has hitherto proved singularly resisting to chromium projectiles.

It will, I trust, have been evident that two of the rarer metals, chromium and nickel, are playing a very important part in our national defences; and if I ever lecture to you again, it may be possible for me to record similar triumphs for molybdenum, titanium, vanadium, and others of these still rarer metals.

Here is another alloy, for which I am indebted to Mr. Hadfield. It is iron alloyed with 25 per cent. of nickel, and Hopkinson has shown that its density is permanently reduced by 2 per cent. by an exposure to a temperature of $-30°$—that is, the metal expands at this temperature.

Supposing, therefore, that a ship-of-war was built in our climate of ordinary steel, and clad with some 3,000 tons of such nickel-steel armour, we are confronted with the extraordinary fact that if such a ship visited the Arctic regions, it would actually become some 2 feet longer, and the shearing which would result from the expansion of the armour by exposure to cold would destroy the ship. Before I leave the question of the nickel-iron alloys, let me direct your attention to this triple alloy of iron, nickel, and cobalt in simple atomic proportions. Dr. Oliver Lodge believes that this alloy will be found to possess very remarkable properties; in fact, as he told me, if nature had properly understood Mendeléef, this alloy would really have been an element. As regards the electrical properties of alloys, it is impossible to say what services the rarer metals may not render; and I would remind you that "platinoid," mainly a nickel-copper alloy, owes to the presence of a little tungsten its peculiar property of having a high electrical resistance which does not change with temperature.

One other instance of the kind of influence the rarer metals may be expected to exert is all that time will permit me to give you. It relates to their influence on aluminium itself. You have heard much of the adoption of aluminium in such branches of naval construction as demand lightness and portability. During last autumn Messrs. Yarrow completed a torpedo boat which was

[1] *Engineering*, vol. lvii., 1894, pp. 465, 530, 595.

built of aluminium alloyed with 6 per cent. of copper. Her hull is 50 per cent. lighter, and she is 3½ knots faster than a similar boat of steel would have been, and, notwithstanding her increased speed, is singularly free from vibration.

Her plates are $\frac{1}{10}$ inch thick, and $\frac{1}{6}$ inch where greater strength is needed. It remains to be seen whether copper is the best metal to alloy with aluminium. Several of the rarer metals have already been tried, and among them titanium. Two per cent. of this rare metal seems to confer remarkable properties on aluminium, and it should do so according to the views I have expressed, for the cooling curve of the titanium-aluminium alloy would certainly show a high subordinate freezing point.

Hitherto I have appealed to industrial work, rather than to abstract science, for illustrations of the services which the rarer metals may render. One reason for this is that at present we have but little knowledge of some of the rarer metals apart from their association with carbon. The metals yielded by treatment of oxides in the electric arc are always carburised. There are, in fact, some of the rarer metals which we, as yet, can hardly be said to know except as carbides. (As the following experiment is the last of the series, I would express my thanks to my assistant, Mr. Stansfield, for the great care he has bestowed in order to ensure success.) Here is the carbide of calcium which is produced by heating lime and carbon in the electric arc. It possesses great chemical activity, for if it is placed in water the calcium seizes the oxygen of the water, while the carbon also combines with the hydrogen, and acetylene is the result, which burns brilliantly. [Experiment shown.] If the carbide of calcium be placed in chlorine water, evil smelling chloride of carbon is formed.

In studying the relations of the rarer metals to iron, it is impossible to dissociate them from the influence exerted by the simultaneous presence of carbon; but carbon is a protean element—it may be dissolved in iron, or it may exist in iron in any of the varied forms in which we know it when it is free. Matthiessen, the great authority on alloys, actually writes of the "carbon-iron alloys." I do not hesitate, therefore, on the ground that the subject might appear to be without the limits of the title of this lecture, to point to one other result which has been achieved by M. Moissan. Here is a fragment of pig-iron highly carburised: melt it in the electric arc in the presence of carbon, and cool the molten metal suddenly, preferably by plunging it into molten lead. Cast iron expands on solidification and the little mass will become solid at its surface and will contract; but when, in turn, the still fluid mass in the interior cools, it expands against the solid crust, and consequently solidifies under great pressure. Dissolve such a mass of carburised iron in nitric acid to which chlorate of potash is added; treat the residue with caustic potash, submit it to the prolonged attack of hydrofluoric acid, then to boiling sulphuric acid, and finally fuse it with potash, to remove any traces of carbide of silicon, and you have carbon left, but—in the form of *diamonds*.

If you will not expect to see too much, I will show you some diamonds I have prepared by strictly following the directions of M. Moissan. As he points out, these diamonds, being produced under stress, are not entirely without action on polarised light, and they have, sometimes, the singular

property of flying to pieces like Rupert's drops when they are mounted as preparations for the microscope. The largest diamond yet produced by M. Moissan is 0·5 mm. in diameter. [The images of many small specimens were projected on the screen from the microscope.]

The close association of the rarer metals and carbon and their intimate relations with carbon, when they are hidden with it in iron, enabled me to refer to the production of the diamond, and afford a basis for the few observations I would offer in conclusion. These relate to the singular attitude towards metallurgical research maintained by those who are in a position to promote the advancement of science in this country. Statements respecting the change of shining graphite into brilliant diamond are received with appreciative interest; but, on the other hand, the vast importance of effecting similar molecular changes in metals is ignored.

We may acknowledge that "no nation of modern times has done so much practical work in the world as ourselves, none has applied itself so conspicuously or with such conspicuous success to the indefatigable pursuit of all those branches of human knowledge which give to man his mastery over matter." [1] But it is typical of our peculiar British method of advance to dismiss all metallurgical questions as "industrial," and leave their consideration to private enterprise.

We are fortunately to spend, I believe, eighteen millions this year (1895) on our Navy, and yet the nation only endows experimental research in all branches of science with four thousand pounds. We rightly and gladly spend a million on the *Magnificent*, and then stand by while manufacturers compete for the privilege of providing her with the armour-plate which is to save her from disablement or destruction. We as a nation are fully holding our own in metallurgical progress, but we might be doing so much more. Why are so few workers studying the rarer metals and their alloys? Why is the crucible so often abandoned for the test-tube? Is not the investigation of the properties of alloys precious for its own sake, or is our faith in the fruitfulness of the results of metallurgical investigation so weak that, in its case, the substance of things hoped for remains unsought for and unseen in the depths of obscurity in which metals are left?

We must go back to the traditions of Faraday, who was the first to investigate the influence of the rarer metals upon iron, and to prepare the nickel-iron series of which so much has since been heard.[2] He did not despise research which might possibly tend to useful results, but joyously records his satisfaction at the fact that a generous gift from Wollaston of certain of the "scarce and more valuable metals" enabled him to transfer his experiments from the laboratory in Albemarle Street to the works of a manufacturer at Sheffield.

Faraday not only began the research I am pleading for to-night, but he gave us the germ of the dynamo, by the aid of which, as we have seen, the rarer metals may be isolated. If it is a source of national pride that research should be endowed apart from the national expenditure, let us, while remembering our responsibilities, rest in the hope that metallurgy will be well represented in the Laboratory which private munificence is to place side by side with our historic Royal Institution.

[1] *The Times*, Feb. 22, 1895.

[2] In the development in the use of these alloys, the *Société Ferro-Nickel*, and *Les Usines du Creusot*, deserve special mention.

METALS AS FUEL.

FRIDAY, February 22, 1901.

[*Proc. Roy. Inst.*, vol. xvi., p. 496.]

A careful metallurgist,[1] writing in the eighteenth century, claimed that "every matter which is combustible either wholly or in part, is called fuel, the pabulum of fire." The word is, however, usually restricted to substances which may be burnt by means of atmospheric air with sufficient rapidity to evolve heat capable of being applied to economic purposes. The latter definition covers certain metals, though it was doubtless framed to include only carbon and associations of carbon and hydrogen, such as coal. The omission from the definition of the reference to atmospheric air would enable the list of metals which might be used as fuel to be widely extended.

It has long been known that metals will burn, and it would be easy to show that the history of inorganic chemistry is epitomised and enshrined in a mass of litharge, which is simply burnt lead. Successive generations of chemists, from Geber in the eighth century to Lavoisier in the eighteenth, studied litharge carefully before the latter proved partly by its aid the identity of respiration, calcination and combustion. Into this history I need not enter, but it may be pointed out that Sir Isaac Newton[2] had a clear idea as to the possibility of burning metals. "Is not fire," he asks, "a body heated so hot as to emit light copiously?" . . . "for what else is red-hot iron than fire?" and he significantly adds, "metals in fusion do not flame for want of copious fume." He was, moreover, aware that a mixture of lead and tin "suitably heated" does emit "fume and flame," and, in fact, a mass of one part tin and four parts lead, which looks metallic, will, if it be kindled, continue to burn like an inferior variety of peat, leaving an ash-like product which may be used as an enamel.

I propose to show that metals may be burnt for the sake of the heat and light they produce, just as ordinary fuels are burnt, except that in burning ordinary fuels combustion is often effected in two distinct steps or stages, in the first of which carbonic oxide is formed, and in the second carbonic acid, the products in both cases being gaseous. When metals are burnt, the products of combustion are solid, or condense to solids, and they, therefore, present a marked contrast to ordinary fuels which, as has just been stated, yield on combustion gaseous products. As I shall have but little to say about the light which attends the combustion of metals, I may as well dismiss the subject by reference to a familiar application of the burning of metals for the purpose of illumination. It is easy to fire electrically a portion of what is known as a "magnesium star," and a "fire-ball" of magnesium attached to a parachute is beautifully packed in this shell, for the loan of which I am indebted to the authorities of the Royal Arsenal, Woolwich, and when the shell explodes the stars burn and illuminate the enemy's position in the darkness of night, so that guns may be laid to place projectiles in the enemy's lines.

[1] C. E. Gellert, "Metallurgic Chemistry," translated by I. S. (London, 1776), p. 74.

[2] "Optic," pp. 316-319, quoted by Shaw in his edition of the works of Boyle, vol. ii., p. 400.

Before proceeding further, I want to use the electric furnace as affording a basis of comparison with the method of producing high temperatures by the combustion of metals, which I shall proceed to show subsequently. A current of 100 amperes at 200 volts is passed by carbon poles into the furnace in which pig-iron is being melted; directly the last piece of iron has become fluid, the temperature of the fused pool must be about 1,300° C. The fluid mass is reflected on the screen merely to give some indication as to the appearance of such a mass at 1,300° C., and not to afford a test of the capabilities of the electric furnace. Later on I hope to show that a far higher temperature can be produced by very simple means in a receptacle of about the same capacity as the laboratory part of the furnace.

Henceforth in the course of this lecture metals will be burnt for the sake of the heat which is the result of their combustion. From this point of view metallurgists have long used metals as fuel, often without due recognition of the fact, but case after case could be cited in which conducting definite metallurgical operations is made possible by burning portions of the metal or metals under treatment. Time will perhaps be saved if I place in sharp contrast the use of ordinary fuel and metallic fuel, even though it takes us rather far back, for I do not want it to be thought that the use of metals as fuel is new, although their adoption for this purpose has recently been greatly stimulated. Here is a mass of very ordinary iron ore picked up on a heath in Surrey, which skirts the site of what was once the ancient forest of Anderida. The prehistoric dweller on the heath who used the beautiful flint arrowheads, which are found near the iron ore, merely burnt the wood of the forest to warm himself or to cook his food. But the Britons whom Cæsar found in Andreaswold smelted iron with the wood of the forest trees, from which they prepared charcoal, and smelting iron was actively conducted in Queen Elizabeth's reign, and even survived into the last century in the district I am contemplating. But in smelting iron, carbon became associated with it and played a subtle part, rendering the iron precious for certain purposes and useless for others. Iron had, therefore, to be "decarburised" with a view to its conversion into steel, and in doing this metallurgists for centuries truly burnt some of the iron itself, using it actually as fuel. I will only add that the use of metals as fuel assumed magnificent proportions in the hands of Bessemer, as may be illustrated by an experiment. A few pounds of a compound of iron, carbon, silicon, and manganese are melted in the wind furnace, which is simply used because it affords a convenient method of melting the mass, which is turned into a small Bessemer converter. A stream of oxygen is directed into the fluid mass. Air would do, but with so small a mass the free nitrogen would cool it too rapidly. In a few seconds the carbon in the fluid will be burnt away: nevertheless the mass gradually becomes hotter and hotter, a shower of sparks rises, and a brilliant pyrotechnic display is the result. The metalloid silicon is now burning, and then brown fumes of iron and manganese pass freely off; these metals are truly burning and are maintaining the heat of the bath, and the presence of their fumes shows that it is time to stop the operation. The temperature is somewhere near 2,000° C., but according to some recent investigations of Prof. Noel Hartley [1] a temperature of more than 2,000° C. is attained in the con-

[1] *Phil. Trans.*, vol. cxcvi., series A, p. 479, 1901.

verter. Bessemer gave the world in 1856 cheap steel; we, therefore, owe to him the inestimable benefits that are the results of that gift, and I ask you to bear in mind that his great service to the industry of which we as a nation are so justly proud rested on the possibility of using metalloids and metals as fuel. I have already promised that in the course of the lecture I will show some experiments in which the temperature will be a thousand degrees higher than in the one you have just seen. In the Bessemer process the products of combustion are both gaseous and solid, and in a very ordinary case the heat engendered by the carbon of the bath which evolves gases is only half that which results from the combustion of the silicon, iron, and manganese which yield solid products. As regards the "open-hearth" process in the phase of it which is known as the "pig and ore" process, oxygen is presented and heat is produced under similar conditions to those we shall consider subsequently in the case of the action of aluminium on ferric oxide.

The following table, which contains the relative calorific powers of different metals and metalloids as compared with carbon, indicates the advantage which certain metals possess over carbon for use as fuel:—

HEAT EVOLVED BY BURNING ONE GRAMME OF THE FOLLOWING ELEMENTS.

Element.	Product of Combustion.	Calories.
Aluminium,	Al_2O_3	7,250
Magnesium,	MgO	6,000
Nickel,	NiO	2,200
Manganese,	MnO_2	2,110
Iron,	Fe_2O_3	1,790
"	Fe_3O_4	1,580
"	FeO	1,190
Cobalt,	CoO	1,090
Copper,	CuO	600
Lead,	PbO	240
Barium,	BaO	90
Chromium,	Cr_2O_3	60
Silver,	Ag_2O	30
Carbon,	CO_2	8,080
"	CO	2,417
Silicon,	SiO_2	7,830

The question at once presents itself—At what temperature will such metals as can be used for fuel begin to abstract oxygen from the air? The answer is—It depends on the method by which the metals are prepared. If they are in a chemically active state, as lead is which has been prepared from the tartrate of lead, they will, in many cases, take fire in air and burn at the ordinary temperature. Such lead burns readily when shaken in air. If this mass of uranium, for which I am indebted to M. Moissan, be filed in air, the detached particles will ignite. Metallic iron which has been reduced by hydrogen from its oxide at a temperature below 700° C. will also take fire and burn in air at the ordinary temperature, a point of extraordinary interest in relation to the allotropy of iron.[1] Metals in this chemically active state are said to be "pyrophoric."

So far as I am aware, metals in this chemically active state have not

[1] Osmond and Cartaud, *Ann. des Mines*, vol. xviii., 1895, p. 113.

been used as fuels. Neither am I aware that any use has been made of the allotropy of metals as enabling them to be used as fuel, but Prof. Graham once told me that pyrophoric iron had been suggested for warming ladies' muffs, the intention being to place the iron in a small receptacle and to admit air gradually as warmth was needed. Sir Henry Trueman Wood also remembers the suggestion, but tells me that he can find no record of it in the *Journal of the Society of Arts*. I may just mention that the burning of metallic antimony plays a very important part in roasting silver ores, and the behaviour of the metal is so peculiar while burning that I must pause to show it you. [A melted globule of antimony, if thrown on to a tray of paper, darts about and cannons from the sides, leaving a track of dark oxide on the paper.]

The metal I am going to employ as fuel is aluminium, the oxygen for its combustion being supplied by metallic oxides, which readily part with their oxygen to aluminium if it be raised to certain definite temperatures. This question of the transference of oxygen from one metal to another, which results in the liberation of the metal attacked, is of special interest to us at the Royal Institution, for it undoubtedly originated within these walls, and is due to Sir Humphry Davy. He discovered potassium in 1807, and in 1809 attempted to remove the oxygen from alumina by heating it with metallic potassium. He says,[1] "if I had succeeded in isolating the metal I should have called it *alumium*." His success was imperfect, but he certainly did obtain, by the intervention of metallic potassium, an alloy of aluminium and iron. It remained for Wöhler to prepare pure metallic aluminium from its chloride in 1827, and for Henri Saint Claire Deville, who began to work in 1854, to establish the metallurgy of aluminium on an industrial scale. As regards the reduction of metals from their chlorides, Wöhler [2] obtained crystalline compounds of chromium and aluminium, and Michel [3] compounds of aluminium with manganese, iron, nickel, tungsten, molybdenum, and titanium. Levy [4] obtained an alloy of titanium and aluminium, Beketoff [5] an alloy of barium with aluminium from the chloride of barium mixed with baryta. Dr. Goldschmidt [6] has given references to these authorities in a recent valuable paper. In 1856, Charles and Alexandre Tissier [7] observed the fact which is the starting point of the experiment I have to show you. They found that aluminium decomposes the oxides of lead and of copper, much heat being evolved by the reaction.

They do not appear to have used aluminium in a finely divided state, and, therefore, failed to reduce certain metals from their oxides which are now known to be perfectly easy to reduce. It was not until comparatively recently that the use of aluminium for separating other metals from their oxides assumed serious proportions. Claude Vautin showed on June 13, 1894, at a soirée of the Royal Society, a few metals, and among them carbon-free chromium and manganese, which he had prepared, and as he undoubtedly gave the impulse that started much of the subsequent work in this direction, it may be well to give the description which was appended to the specimens he showed. It runs as follows:—

[1] *Phil. Trans.*, part i., 1810, p. 60.
[2] *Ann. der Chemie*, vol. cvi., p. 118.
[3] *Ibid.*, vol. cxv., p. 102; *ibid.*, vol. cxiii., p. 248.
[4] *Comptes Rendus*, vol. cvi., p. 66.
[5] *Ann. der Chemie*, vol. cx., p. 374.
[6] *Ibid.*, vol. ccci., p. 19.
[7] *Comptes rendus*, vol. xliii., 1856, p. 1187.

Specimens of Metallic Chromium, Manganese, Tungsten, Iron, etc., free from Carbon; also fused Alumina, obtained during the reduction of the metallic samples.

"The specimens of metallic chromium, manganese, etc., have been reduced from their oxides by means of metallic aluminium. The oxide of the metal to be reduced is intimately mixed with finely divided aluminium, and heated in magnesia-lined crucibles. The heat produced by the oxidation of aluminium during the operation is sufficient to fuse alumina, a specimen of which is exhibited."

The subject is, however, in a sense your own, for, as far as I know, the lecture on "The Rarer Metals and their Alloys,"[1] which I delivered here in 1895, was the first occasion on which the reducing action of aluminium was demonstrated on a comparatively large scale, and covered an extended series of metallic oxides. Since that time great progress has been made, the most noteworthy advance being in the direction of the use of aluminium for the sake of the heat afforded by its combustion as a true fuel, the oxygen being derived, not from the air, but from a metallic oxide. In order that I may be clear, let me repeat that when coal is burnt the oxygen is derived from the air. When aluminium is used as a fuel the oxygen is derived from a metallic oxide, the metals change places: the aluminium is oxidised, and the other metal set free from its oxide. This part of the subject must be carefully approached, and the question at once arises as to what extent the aluminium must be heated before it will begin to abstract oxygen from air or from an oxide. It is well known that the metal aluminium will not oxidise sensibly in the air at the ordinary temperature, but the presence of a little mercury enables it to oxidise readily. Le Bon[2] has shown how minute the quantity of mercury may be. This wire of aluminium to which a thermo-couple is attached will, if a mere trace of mercury be rubbed on its surface, become rapidly heated by oxidation, the temperature rising to 102° C., while at the same time a fungoid-like growth of alumina forms on its surface. Aluminium foil will burn readily in oxygen if its combustion be started by a glowing fragment of charcoal. The temperature at which aluminium will abstract oxygen from a metallic oxide will depend on the oxide submitted to its action. Three cases may be taken: (1) Lead oxide and granulated aluminium may be ignited by a match, as may also silver oxide (Ag_2O), for it parts with its oxygen very readily. (2) Chromium oxide (Cr_2O_3) and granulated aluminium burn slowly and require rather a high temperature to start the reaction. Oxide of iron (Fe_2O_3) and granulated aluminium also require the presence of a readily reducible oxide to start the reaction. On the other hand, (3) a mixture of sodium peroxide, carbide of calcium, and granulated aluminium may be started by a drop of water by the mere inflammation of the acetylene. In all these cases, or in any other case, the products are solid, for if any of the reduced metal is volatilised it soon condenses, and may be collected, usually in an oxidised form.

[1] *R. Inst. Proc.*, vol. xiv., p. 497. *Nature*, vol. lii., pp. 14 and 39.
[2] *Comptes Rendus*, vol. cxxxi., p. 707.

In using aluminium as fuel the object, of course, is to produce intense heat, and, returning to this mass of iron ore from the Surrey heath, it may at once be stated that an oxide of iron, ferric oxide, is the most convenient oxide to use, partly because it is inexpensive.

Many of my audience already know that the recent investigations having for their object the use of aluminium as a source of heat have been conducted by Dr. Hans Goldschmidt, of Essen, and it is through his labours that metallurgy enters upon an entirely new phase. It would be difficult to offer him fuller or more unstinted praise than that. You will, I trust, soon realise how much this branch of metallurgical industry is indebted to him. In its simplest form his process consists in igniting a mixture of oxide of iron, ferric oxide and finely divided aluminium. To this mixture the name of "thermit" has been given, and several varieties of it, adapted to various kinds of work, are used by Dr. Goldschmidt at the works of the Allgemeine Thermit-Gesellschaft at Essen-Ruhr.

The mixture is placed inside a crucible and is ignited by a small piece of magnesium wire, which serves as a kind of wick if it is placed in a little heap of calcium sulphate and aluminium. Such a mass will now be lighted, and you see intense heat is produced. [When the operation was conducted in accordance with the above indications, the theatre was brilliantly illuminated by the intense light produced. A mass of metallic chromium weighing about 100 lbs. reduced to the metallic state as above described, was exhibited.] The aluminium abstracts oxygen from the oxide of iron, and a sufficiently intense heat is produced, not only to melt the iron which is liberated from its oxygen, but to melt up the slag and, further, to leave a considerable surplus of heat, which is available for doing other work. No known pyrometer will enable the heat to be measured. I believe it to be about 3,000° C.

The aluminium plays the part of a fuel, and this table shows the advantage aluminium possesses as compared with carbon for the particular work required of it.[1]

THE REDUCTION OF Fe_2O_3 TO IRON BY ALUMINIUM AND BY CARBON.

	Aluminium.	Carbon.
Compound produced,	Al_2O_3	CO
Amount of reducing agent required to produce 1 kilo of iron,	0·484 kilo	0·321 kilo
Amount of heat produced by oxidation of the reducing agent,	3,456 calories	770 calories
Heat required to reduce the Fe_2O_3,	1,796 ,,	1,796 ,,
,, for fusion of the slag,	518 ,,	
,, ,, iron,	362 ,,	
Total heat required,	2,706 ,,	1,796 ,,
Residual heat available,	750 ,,	—1,026 ,,

[1] These data are from a paper by Prof. Kupelwieser, of Loeben, *Oesterreichische Zeitschrift für Berg. und Hüttenwesen*, vol. xlvii., 1899, pp. 145-149.

On the aluminium side some 750 calories (units of heat) are available to do work (3,456 − 2,706 = 750 calories). On the carbon side there is a deficiency of no less than − 1,026 calories. As regards the crucibles, they may be made of alumina, the solid product which is the result of the combustion of aluminium. They may also be made of magnesia or mended with magnesia. I shall have more to say about the solid product of the combustion subsequently. The practical application of the process is as follows:—The ignited and molten mass in the crucible is so intensely hot that it may be made to unite surfaces of steel that require to be joined, such as the ends of lengths of rails. It may be objected that the fluid contents of the crucible would set as a whole round the metallic junction and give trouble, but this is not the case, for a layer of fluid alumina appears both to coat the rod, tube, or rail which has to be welded, and to set in a mass which can be readily detached after the work is done.

As regards the comparison of the use of aluminium as fuel with the electric arc, M. Camille Matignon,[1] in a very interesting discourse recently delivered in Paris, has instituted a comparison between the Goldschmidt process and electric furnace. Quoting Moissan,[2] he shows that in reducing titanic acid by carbon in the electric furnace having a "laboratory space" of 800 c.c., 300 horse-power absolute were employed, producing per second 190,500 calories by burning 1·08 kilograms of aluminium. On the other hand, by burning 3·2 kilograms of ferric oxide during one minute in a crucible of about the same capacity as the laboratory of the electric furnace, the rate of evolution of heat is equivalent to 375 horse-power absolute; the latter process does not, however, work continuously, but could readily be made to do so. It should be pointed out that an impure variety of aluminium can be used, and that if the heat needed to effect a given operation is but moderate, the aluminium may be diluted by the presence of an inert substance.

[A description was then given of the use of thermit in effecting welds and in repairing defective castings.]

Manganese and chromium containing only small quantities of carbon are now produced on a large scale for industrial use. As regards the reduction of metals and alloys from their oxides by burning aluminium, the following are the more recent results that have been obtained.[3] The use of carbon-free chromium in connection with the metallurgy of steel is an exceedingly useful development of the methods we have considered. Hitherto, the addition of ferro-chrome to steel has involved a loss of from 20 to 25 per cent. of the chromium while with pure chromium the loss is slight. Moreover, the addition of ferro-chrome incidentally raises the percentage of carbon, and steel containing, for instance, 2·5 per cent. of chromium should not have more than from 0·15 to 0·20 per cent. of carbon, and this can only be attained by the use of pure chromium. In the manufacture, also, of tool steel, the percentage of chromium may reach from 6 to 10 per cent. and even higher, a result which is only rendered possible by the use of pure chromium. In the same way, in connection with the metallurgy of copper, the possibility of pro-

[1] *Moniteur Scientifique Quesneville*, 4 S. vol. xiv., part i., pp. 357 *et seq.*
[2] "Le Four électrique," p. 19.
[3] *Stahl und Eisen*, March 24, 1901.

viding carbon-free manganese is important, as is also the preparation of cupro-manganese free from iron. Alloys of manganese with zinc and with tin are likely to prove of value. Many uses have been found for the alloy containing 80 per cent. of zinc and 20 per cent. of manganese, while it is anticipated that the alloy containing 50 per cent. of tin and 50 per cent. of manganese will also prove to be important. Use has also been found for an alloy of 70 per cent. manganese and 30 per cent. chromium. Ferro-titanium, with 20 to 25 per cent. of titanium, and alloys of titanium and manganese containing from 30 to 35 per cent. of titanium, have also been produced. Titanium, moreover, absorbs nitrogen, and ferro-titanium is found to be very useful in producing sound steel castings. Quite independently of Dr. Goldschmidt, I succeeded in the preparation of alloys of iron with from 3 to 25 per cent. of boron, the alloy containing 3 per cent. of boron proving to be beautifully crystallised. Dr. Goldschmidt states that definite results have not been obtained in attempts to utilise it. I am still investigating this most interesting subject. Dr. Goldschmidt has obtained ferro-vanadium, the best results being obtained with steel containing 0·5 per cent. of vanadium. He also prepared an alloy of lead and barium containing 30 per cent. of barium, which affords an example of the possibility of forming alloys of metals with those of the alkaline earths by this process.

It only remains for me to direct your attention to the nature of the solid product of the combustion of aluminium, which is alumina often of a high degree of purity, and in a specially interesting form. The alumina from the reduction of oxide of chromium, when it is allowed to cool, forms large ruby-tinted crystalline masses, closely resembling the natural ruby. I have now to show you on the screen some rubies and sapphires produced as an incident of this beautiful process. The blue sapphire mass is, however, only translucent, not transparent. The ruby crystals are often very beautiful, as these slides show. Rubies placed in a vacuum tube and subjected to the bombardment of an electric discharge are, as Sir William Crookes has taught us, beautifully phosphorescent. I have here in this tube some thin crystalline plates of artificial ruby; they become beautifully phosphorescent when the current from the induction coil is passed through the tube, and by the kindness of Sir William Crookes I can show you some true rubies treated in a similar way. The behaviour of the artificial rubies in the vacuum tube is not quite as brilliant as that of the natural ones, but hitherto no special attention has been devoted to their preparation; they are simply thin plates broken from a large crystalline mass of slag such as that on the table. I may add that this variety of corundum produced by the burning of aluminium is very hard, and may be used, not only for the same purposes as ordinary corundum, but for lining the crucibles in which the operations are conducted, so that the product of combustion takes its place in conducting the process. My warmest thanks are due to Dr. Goldschmidt for lending me the beautiful specimens on the table, and to Mr. W. H. Merrett for his aid in conducting the experiments.

I have set before you the considerations respecting the use of metals as fuel simply as they appear to flow. I trust that the adoption of the title of this lecture has been justified by the evidence given as to the possibility of using metals as fuel in the strictest sense of the word. It is well to be accurate on this point, because we are told that the first known appearance

of the word "fuel" in the English language occurs in a poem [1] and seems to have been a misinterpretation of the old French word *fouaille*, and was adopted in the belief that sustenance for the body and food for the flames are synonymous. Widening our view of metals by grouping them with fuels will be acceptable, because fire and flame powerfully appeal to our thoughts. We "kindle" enthusiasm, and add "fuel" to the fire of ambition—we constantly use fire, flame and fuel as similes, and any prospect of extending their use to us as such by enlisting metals in the service will be welcome. An early Italian metallurgist, Vanoccio Biringuccio, might not have thought so, for I find that, writing in the sixteenth century, he quaintly devotes the last chapter of a work on metallurgy to "Fires which burn and leave no ashes."[2] In this chapter he appeals to envy, hatred, malice, and other products of a kindled imagination, and traces their analogies to fuel and flame, but he speedily takes leave of his readers in alarm at the prospect such a treatment of the subject presents.

The burning of aluminium as fuel gives us sapphires and rubies in the place of ashes, and metallic fuel is burnt, not by the air above but by the oxygen derived from the earth beneath, as it occurs in the red and yellow oxides to which our rocks and cliffs owe their colour and their beauty.

[1] Cœur de Lion, fifteenth century.

[2] "De la Pirotechnia," 1540, p. 167. (Venice.) "Del fuocho che consuma et non a cenere."

Plate XXIII.]

[*To face page* 361.

Plaque by G. W. De Saulles.

VIII.

ART METAL WORK.

The Colours of Metals and Alloys—Bibliography of Lectures on Alloys and Art Metal Work.

THE COLOURS OF METALS AND ALLOYS.[1]

A Lecture delivered on September 3, 1886, *to the Operative Classes in the Town Hall of Birmingham in connection with the Meeting of the British Association.*

I BEGIN with no ordinary pleasure the work which has been intrusted to me by the Council of the British Association. It is nearly twenty years since this series of lectures was established. The first, on "Matter and Force," was delivered at Dundee by a brilliant experimenter and one of the most eloquent living exponents of science; it was followed, at Norwich, by a lecture by Prof. Huxley, to whom the nation owes a deep debt of gratitude for his intense sympathy with all who are seeking to widen the bounds of scientific knowledge—to be whose colleague in one of the most important scientific schools of the country is my great good fortune. These lecturers were succeeded by other eminent men, among whom may be mentioned Spottiswoode, Bramwell, and Lubbock. The object of the lectures is to diffuse a knowledge of the operations of Nature, and to add to the number of those who rejoice in her works. Many, therefore, who have spoken to audiences similar to this, have appealed to natural phenomena; and instead of talking to you about the colour of metals, I also should have liked to dwell on the colour of the sea and sky, but Ruskin's works are, I know, often in your hands, and he has told you once for all of the colour of clouds that "there is not a moment of any day of our lives when Nature is not producing scene after scene, picture after picture, glory after glory, and working still upon such exquisite and constant principles of the most perfect beauty that it is quite certain it is all done for us, and intended for our perpetual pleasure."[2] The metallurgist, however, cannot speak with authority on themes such as these; and I have, therefore, selected a subject which will, I believe, enable me to bring before you important truths affecting a wide range of industrial operations, and at the same time to sustain the true function of art by pointing to the direction in which we may have increased pleasure in things that constitute our most ordinary possessions, and which we use in daily life. First permit me to explain that I intend to include under the title of the lecture any facts which are, in my opinion, connected with the colours of

[1] *Nature*, Dec. 2, 1886.
[2] "Modern Painters," vol. i., part 2, 1851, p. 201.

metals and alloys, whether natural to them or produced by artifice, as well as a brief examination of the influence which the colours of metals appear to have exerted on the history of science.

I propose to begin at what will appear to be a somewhat remote starting point. We say that copper is red, gold yellow, and silver white, but it is by no means certain that the early races of the world had any very clear perception of the difference between these several metallic colours. With regard to early Hebrew and Greek civilisation, Mr. Gladstone has expressed his belief that the colour sense—that is, the power of recognising colour and distinguishing it from mere brightness or darkness—was imperfectly developed, and he considers that "the starting point is absolute blindness to colour in the primitive man," and he urges that the sense of colour has been gradually developed "until it has now become a familiar and unquestioned part of our inheritance." He adds: "Perhaps one of the most significant relics of the older state of things is to be found in the preference (known to the manufacturing world) of the uncivilised nations for strong and, what is called in the spontaneous poetry of trading phrases, loud colour." [1]

Dr. Magnus holds the view that the colour sense in man has undergone a great improvement within the last 2,000 years, and Prof. Haeckel supports this speculation, but it is opposed by Romanes, who has favoured me with some observations on the subject, in view of this lecture; and it seems to me strange, if savage nations are really deficient in the sense of colour, that the use of such colours as they can get in metals and fabrics, blended, for instance, in a war club or a pipe stem, should be so thoroughly "understood" and so discriminatingly employed as we sometimes find them to be. It may further be observed that primitive man may even have derived from his more remote ancestry some power of being influenced by colour, and we are told that the attraction which gorgeous colouring in flowers has for birds and insects, and which colour generally possesses for our nearer ancestors, has been of great importance in the origin of species, and in the maintenance of organic life.

No doubt, in ancient times, there was much confusion between mere brightness and colour, such as is evident in the beautiful sentence in which St. Augustine [2] says: "For this *queen of colours, the light*, bathing all which we behold, wherever I am through the day, gliding by me in varied forms, soothes me when engaged on other things and not observing her." If, however, it were proved that the power of distinguishing the colour of metals was not widely diffused among the Egyptians, Hebrews, and Greeks, it is at least certain that there were individuals of these nations to whom, in very early times, the colour of metals was all-important; and although they may have confused different precious stones under generic names, they certainly appreciated their various colours, and knew, moreover, that by fusing sand with the addition of a small quantity of certain minerals, they could produce artificial gems of varied tints.

My object in leading you so far back—in discussing what appears to be a very matter-of-fact subject—is to point to the close connection between the early recognition and appreciation of colour in metals or minerals, and the foundation of the science of chemistry.

[1] *Nineteenth Century*, p. 367, 1877.
[2] "Confessions of St. Augustine." Edition edited by E. B. Pusey, D.D. (p. 211).

In early scientific history the seven metals known to the ancients were supposed to be specially connected with the seven principal planets whose names they originally bore, and whose colours were reflected in the metals; thus gold resembled the sun, silver the moon, while copper borrowed its red tint from the ruddy planet Mars. The belief in the intimate relation between colours and metals, the occult nature of which they shared, was very persistent, and we find a seventeenth-century writer, Sir John Pettus, saying[1] that "painters" derive "their best and most proper colours from metals whereof seven are accounted the chief, produced from the seven chief metals, which are influenced by the seven planets." A survival of this feeling is suggested by a modern writer, Leslie, who supposed that "when Newton attempted to reckon up the rays of light decomposed by the prism, and ventured to assign to them the famous number seven, he was apparently influenced by some lurking disposition towards mysticism."[2]

It would be impossible for me to overrate the importance of the colour of metals in relation to scientific history, for the attempt to produce a metal with the colour and properties of gold involved the most intense devotion to arduous research, sustained by feverish hope, attended by self-deception and elaborate fraud, such as hardly any other object of human desire has developed. It led to despair, to madness, and to death; but finally, through all, alchemy prepared the way for the birth of chemistry, and for the true advancement of science.

In early times, as now, gold was an extremely desirable form of portable property, and its colour was, perhaps, held to be the most distinctive and remarkable fact about it. I may incidentally observe that the dominant idea of colour in connection with the metallic currency survives in the familiar phrase, "I should like to see the *colour* of his money," which curiously expresses a desire, tempered by doubt as to its fulfilment. On looking back, we find that, at least from the third to the seventeenth century, the colour of gold haunted the early experimenters, and induced them to make the strangest sacrifices, even of life itself, in the attempt to imitate, and even actually to produce, the precious metal. Let us see what kind of facts were known within the period I have indicated. In barbaric times, hammered pieces of gold, or gold beaten into thin sheets and plates, were used with coloured stones and coral for personal adornment. The next step was to make gold go further by gilding base metals with it, and, in order to do this, the colour was for the moment sacrificed by combining the gold with quicksilver. This was done at least in the time of Vitruvius, B.C. 80, heat being used to drive away, as vapour, the quicksilver which had been united to the gold, leaving a thin film of precious metal on the surface to be gilded. But this was possibly not the first method of gilding, for we now know, from a papyrus of about the third century[3] of our era, that lead was used for this purpose. Gold, when fused with lead, entirely loses its golden colour, and yet, by the application of heat in air, the lead may be made to flow away as a fusible oxide.

[1] "Fleta Minor," 1686, Appendix, "Essay on Metallic Words—Colour."

[2] "Treatises on Various Subjects of Natural and Chemical Philosophy."

[3] "Les Origines de l'Alchimie," par M. Berthelot, 1885, pp. 82, 89. It is interesting to compare the account of this method of gilding by lead with the expression used by Homer, who says: "As when gold is *fused* around the silver by an experienced man."—"Odyssey," vi., 232-35, quoted by Schliemann, "Ilios," p. 258, in relation to a gilded knife of copper which he permitted me to analyse in 1878.

leaving the precious metal on the metallic object to be gilt, the base metal being as it were transmuted, superficially at least, into gold. The point I want to insist upon is that the metallic colour of the gold vanished during the process as carried on by the craftsman, only to reappear at the end of the operation; and I am satisfied that it was from such simple technical work as this that the early chemists were led to think that the actual production of gold—the transformation of base metals into gold—was possible. The more observant of them, from Geber, the great Arabian chemist of the seventh century, to our own countryman, Roger Bacon, in the thirteenth, saw how minute a quantity of certain substances would destroy the red colour of copper, or the yellow colour of gold. A trace of arsenic will cause the red colour of copper to disappear; therefore, the alchemists very generally argued, some small quantity of the right agent, if only they could find it, will turn a base metal to the colour of gold. Look, they said, how small a quantity of quicksilver will change the appearance of metallic tin. Here is a bar of tin, 2 feet long and 1 inch thick, which it would be most difficult to break, though it will readily bend double. If only I rub a little quicksilver on its surface a remarkable effect will be produced, for the fluid metal will penetrate the solid one,[1] and in a few seconds the bar will, as you see, break readily, the fractured surface being white, like silver. It was by such facts as this that men were led to believe that the white metal, silver, could be made.

Successive workers at different periods held divergent views as to the efficacy of the transmuting agent. Roger Bacon, in the thirteenth century, held that one part of the precious substance would suffice to turn a million parts of base metal into gold. Basil Valentine, in the fourteenth century, would have been content with the transmutation of seventy parts of base metal by one part of the agent. While, coming to the end of the eighteenth century, Dr. J. Price, F.R.S., of Guildford, only claimed that the substance he possessed would transmute from thirty to sixty parts of base metal.[2]

It is a curious fact that no one seems to have actually prepared the transmuting agent for himself, but to have received it in a mysterious way from "a stranger"; but I must not dwell on this. I will merely point out how persistent was the view as to the singular efficacy of the transmuting agent, and I will content myself with a reference to Robert Boyle, our great countryman, an accurate chemist of the seventeenth century, who did more than any one else to refute the errors of alchemy. He nevertheless characteristically records[3] the following experiment, in which, instead of ennobling a base metal, he apparently degraded gold to a base one. He first purified a small quantity of gold, about "two drachms," with great care, and, he states, "I put to it a small quantity of powder communicated to me by a stranger"—it is singular that even he should have received the transmuting agent in the usual way—"and," he adds, "continuing the metal a quarter of an hour on the fire, that the powder might diffuse itself through it, . . . the metal when cold appeared to be a lump of *dirty colour*; . . . 'twas brittle, and, being worked with a hammer, it flew into several pieces. From hence," he

[1] Homberg, *Mém. de l'Acad. Royale des Sciences*, 1713 (vol. published 1739), p. 306.

[2] "An Account of some Experiments on Mercury, Silver, and Gold made at Guildford, in the Laboratory of James Price, M.D., F.R.S.," Oxford, 1782.

[3] "The Philosophical Works of the Hon. Robert Boyle" (Shaw's second edition), 1738, vol. i., p. 78.

adds, "it appears that an operation almost as strange as that called 'projection'" (or transmutation) "may safely be admitted, since this experiment shows that gold, . . . the least mutable of metals, may in a short time be exceedingly changed . . . by so small a portion of matter that the powder transmuted a thousand times its weight of gold." He elsewhere observes of a similar experiment, "transmutation is, nevertheless, real for not being gainful; and it is no small matter to remove the bounds which Nature seems very industriously to have set to the alterations of bodies." [1] The change in the colour of the gold was remarkable, but Boyle had only produced one of the series of alloys most dreaded by every jeweller—"brittle gold"—for the way in which an alloy of gold and copper is affected by a small quantity of impurity presents one of the most serious difficulties in working gold. It has been known since the seventh century that minute quantities of certain metals change the colour of gold and render it brittle, and it may be well to demonstrate the fact.

Here are two hundred sovereigns: I will melt them and will add in the form of a tiny shot a minute portion of lead amounting to only the 2000th part of the mass, first, however, pouring a little of the gold into a small ingot, which we can bend and flatten, thus proving to you that it is perfectly soft, ductile, and workable. The rest of the mass we will pour into a bar, and now that it is sufficiently cold to handle, you see that I am able to break it with my fingers, or at least with a light tap of a hammer. The *colour* of the gold is quite altered, and has become orange-brown, and experiments have shown that the tenacity of the metal—that is, the resistance of the gold to being pulled asunder—has been reduced from 18 tons per square inch to only 5 tons. These essential changes in the property of the metal have been produced by the addition of a minute quantity of lead. I have cited these facts mainly to show that the changes produced in the colour and properties of metals by small variations of composition were such as to lead the alchemists on in their belief that it was possible to change lead or tin into gold, and the hope in which they worked enabled them to gather facts out of which chemical science was gradually constructed. We shall see presently that changes in the colour of metals and alloys produced by the addition of small quantities of foreign matter, are of great importance in the application of metals to artistic purposes, but we must first try to examine more closely some of the prominent facts connected with the colour of metals—that is, the effect metals have on light so as to produce the effect of colour in our eyes. We are apt to think of gold as being essentially and distinctively golden-yellow; it may, however, possess a wide range of colours without in any way losing the condition of absolute metallic purity, its relations to light depending entirely on the nature of its surface, and especially on whether the metal is in mass or in a more or less fine state of division. Interesting as gold is to us in mass, it is perhaps still more interesting to us when beaten so fine that a single grain, of the value of 2d., would cover a space of 48 square inches, or when it is so finely divided that the dimensions of a single particle may closely approximate to those of the ultimate atom.

This aspect of the question was investigated by Faraday, and the experimental part of the subject remains practically unadded to since his time.

[1] "The Philosophical Works of the Hon. Robert Boyle" (Shaw's second edition), 1738, vol. i., p. 262.

It is well known that a leaf of gold when seen by transmuted light is either green or blue, according to its thickness.

Gold may readily be converted into a soluble chloride which produces a beautiful golden solution. If such a solution contains very little gold, not more than 2 grains in a gallon, and if certain chemical methods be adopted to precipitate the gold—that is, to throw it out of solution in a *solid*, though in a very fine state of division, the metal may exhibit a wide range of tint, from ruby to black.

[A few drops of phosphorus dissolved in bisulphide of carbon had been added to about a gallon of a very dilute solution of chloride of gold contained in a tall glass cylinder. The beam from an electric light, thrown through the vessel, revealed in the lower part the presence of finely divided metal of the natural golden colour, while the more finely divided gold in suspension imparted a brilliant ruby colour to the liquid, and a glowing ruby disc was projected on a white screen.]

When gold is in the "ruby" state, it is so finely divided that each particle probably approximates to the dimensions of the gold atom.

[The spectrum was then thrown upon the screen, and the audience was invited to compare it with a diagram which, while closely resembling the solar spectrum, really represented the way in which pure metallic gold, prepared by various methods, is capable of behaving in relation to light so as to possess a wide range of colours.]

It would be easy to show that light is similarly affected by other metals; but I have selected gold for the purpose of illustration because it is easy to maintain it in a state of purity, however finely divided it may be. We must, therefore, modify any views we may have formed as to a metal having exclusively a special colour of its own, because it will be evident that a particular colour is only due to a definite state of arrangement of its particles. The intimate relation between the state of the surface of a metal and its colour is well shown by the beautiful buttons devised by Sir John Burton. He proved that if very fine lines be drawn close together, so that 2,000 would be ruled in the space of an inch, a beautiful iridescent effect is produced, the tints being quite independent of the metal itself but due to an optical effect of the lines.

[The image of such a button was then thrown upon the screen.]

Let us now examine some effects of uniting metals by fusing them together into what are called alloys; and, second, the direct influence of a minute quantity of one metal in changing the mass of another in which it is hidden, and causing it to behave in a different way in relation to light, and consequently to possess a colour different from that which is natural to it; or the added metal may so change the chemical nature of the metallic mass that varied effects of colour may be produced by the chemical combinations which result from the action of certain "pickling" solutions. This portion of the subject is so large that I can only hope to set before you certain prominent facts.[1]

First, with reference to the colour produced by the union of metals. Here is a mass of red copper, and here one of gray antimony: the union of the

[1] A list of books and papers dealing with the colours of metals and alloys, and with the production of coloured patina, is given by Prof. Ledebur in his work, "Die Metallverarbeitung," p. 285, 1882, published in Bolley's "Technologie."

two by fusion produces a beautiful violet alloy when the proportions are so arranged that there is 51 per cent. of copper and 49 per cent. of antimony in the mixture. This alloy was well known to the early chemists, but unfortunately it is brittle and difficult to work, so that its beautiful colour can hardly be utilised in art. The addition of a small quantity of tin to copper hardens it, and converts it, from a physical and mechanical point of view, into a different metal. The addition of zinc and a certain amount of lead to tin and copper confers upon the metal copper the property of receiving, when exposed to the atmosphere, varying shades of deep velvety brown, characteristic of the bronze which has from remote antiquity been used for artistic purposes. But by far the most interesting copper alloys, from the point of view of colour, are those produced by its union with zinc—namely, brass. Their preparation demands much care in the selection of the materials, and I might have borrowed from the manufacture of brass instance after instance of the influence of traces of impurity in affecting the properties of the alloy, but it is unnecessary to dwell upon this alloy in Birmingham, for in all that relates to the mechanical manipulation of the alloys of copper with tin and with zinc, you are masters. I have many inducements in this place to speak about this beautiful alloy. I am proud to be a namesake of the craftsman, William Austen, who, in 1460, made that magnificent monument in brass which covers the remains and commemorates the greatness of Richard Beauchamp, Earl of Warwick, and I am glad to remember that Queen Elizabeth granted the first patent for the manufacture of brass in England to William Humfrey, Assay Master of the Mint, a predecessor in the office it is my privilege to hold.

I want, however, to direct your attention to-night to some alloys of copper with which you are probably less familiar than with brass. In this direction Japanese art affords a richer source of information than any other. Of the very varied series of alloys the Japanese employ for art metal work, the following may be considered to be the most important and typical. The first is called "shaku-dō"; it contains, as you will observe from Analyses I.

Shaku-dō.

I.		II.	
Copper,	94·50	Copper,	95·77
Silver,	1·55	Silver,	0·08
Gold,	3·73	Gold,	4·16
Lead,	·11		100·01
Iron and arsenic,	traces		
	99·89		

and II.,[1] in addition to about 95 per cent. of copper, as much as 4 per cent. of gold. It has been used for very large works. Colossal statues are made of it; one cast at Nara in the seventh century being specially remarkable. The quantity of gold is, however, very variable; specimens I have analysed contained only 1·5 per cent. of the precious metal. The next alloy to which I would direct your attention is called "shibu-ichi." There are numerous varieties of it, but in both these alloys, shaku-dō and shibu-ichi, the point

[1] Analyses Nos. I. and III. are by Mr. Gowland, of the Imperial Japanese Mint at Osaka; Nos. II. and IV. by Prof. Kalischer, *Dingl. Polyt. Journ.*, vol. ccxv., p. 93.

Shibu-ichi.

III.		IV.	
Copper,	67·31	Copper,	51·10
Silver,	32·07	Silver,	48·93
Gold,	traces	Gold,	·12
Iron,	·52		
	99·90		100·15

of interest is that the precious metals are, as it were, sacrificed in order to produce definite results; gold and silver, when used pure, being employed very sparingly to heighten the general effect. In the case of the shaku-dō, we shall see presently the gold appears to enable the metal to receive a beautiful rich purple coat or *patina*, as it is called, when treated with certain pickling solutions; while shibu-ichi possesses a peculiar silver-gray tint of its own, which, under ordinary atmospheric influences, becomes very beautiful, and to which the Japanese artists are very partial. These are the principal alloys, but there are several varieties of them, as well as combinations of shaku-dō and shibu-ichi in various proportions, as, for instance, in the case of kiu-shibu-ichi, the composition of which would correspond to one part of shaku-dō rich in gold, and two parts of shibu-ichi rich in silver. Interesting effects are produced by pouring two alloys of different tints together just at the solidifying point of the less fusible of the two, so that the alloys unite but do not blend, and a mottled surface is the result. These alloys are introduced into almost every good piece of metal work.

Now as to the action of pickling solutions. Many of you will be familiar with the mysteries of the treatment of brass by "dipping" and "dead dipping," so as to produce certain definite surfaces, but the Japanese art metal workers are far ahead of their European brothers in the use of such solutions.

The South Kensington Museum contains a very valuable series of fifty-seven oblong plates, some plain and others richly ornamented, which were specially prepared as samples of the various metals and alloys used by the Japanese. The Geological Museum in Jermyn Street has a smaller, but very instructive, series of twenty-four plates presented by an eminent metallurgist, the late Mr. Hochstätter-Godfrey. From descriptions accompanying the latter, and from information I have gathered from certain Japanese artificers now in London, it would appear that there are three solutions generally in use. They are made up respectively in the following proportions, and are used boiling:—

	I.	II.	III.
Verdigris,	438 grains.	87 grains.	220 grains.
Sulphate of copper,	292 ,,	437 ,,	540 ,,
Nitre,	..	87 ,,	..
Common salt,	..	146 ,,	..
Sulphur,	..	233 ,,	..
Water,	1 gallon.	..	1 gallon.
Vinegar,	..	1 gallon.	5 fluid drachms.

That most widely employed is No. 1. When boiled in No. III. solution, pure copper will turn a brownish-red; and shaku-dō, which, you will remember, contains a little gold, becomes purple; and now you will be able to appreciate the effect of small quantities of metallic impurity as affecting the colour

resulting from the action of the pickle. Copper containing a small quantity of antimony gives a shade very different from that resulting from the pickling of pure copper. But the copper produced in Japan is often the result of smelting complex ores, and the methods of purification are not so perfectly understood as in the West. The result is that the so-called "antimony" of the Japanese art metal workers, which is present in the variety of copper called "kuromi," is really a complex mixture containing tin, cobalt, and many other metals, so that a metal worker has an infinite series of materials at command with which to secure any particular shade; and these are used with much judgment, although the scientific reasons for the adoption of any particular sample may be hidden from him. It is strictly accurate to say that each particular shade of colour is the result of minute quantities of metallic impurity, and these specimens and diagrams will, I trust, make this clear, and will prove that the Japanese arrange true pictures in coloured metals and alloys.

[This portion of the subject was illustrated with much care by coloured diagrams representing specimens of Japanese art metal work, by photographs projected on the screen, as well as by the reflected images of small ornaments made of the alloys which had been specially referred to. There was also a trophy of large leaves of copper of varying degrees of purity coloured brilliantly by one or other of the "pickles" above described.]

There is one other art material to the production of which I hope art workmen in Birmingham will soon direct their attention, as its applications are endless. It is called in Japanese "mokumē," which signifies "wood-grain." It is now very rare even in Japan, but formerly the best specimens appear to have been made in Nagoya by retainers of the Daimio of Owari. I have only seen six examples, and only possess a single specimen of native work, and have, therefore, had to prepare a few illustrations for you in soldered layers of gold, silver, shibu-ichi, shaku-dō, and kuromi.

[A diagram showed the method of manufacture.] Take thin sheets of almost any of the alloys I have mentioned, and solder[1] them together layer upon layer, care being taken that the metals which will present diversity of colour come together. Then drill conical holes of varying depth in the mass, or devices in trench-like cuts of V section, and hammer the mass until the holes disappear; the holes will thus be replaced by banded circles and the trenches by banded lines. A Japanese artificer taught me to produce similar effects by taking the soldered layers of the alloy, and by the aid of blunted tools making depressions on the back of the mass so as to produce prominences on the front. These prominences are filed down until the sheet is again flat; the banded alloys will then appear on the surface in complicated sections, and a very remarkable effect is produced, especially when the colours of the alloys are developed by suitable "pickles." In this way any device may be produced. In principle the method is the same as that which produces the *damascening* of a sword-blade or gun-barrel, and depends on the fact

[1] The following solder was found to answer well:—

Silver,	55·5
Zinc,	26·0
Copper,	18·5
	100·0

that under certain conditions metals behave like viscous solids, and as truly "*flow*" as pitch or honey does, and in the case of mokumē the art workman has a wide range of tinted metals at command.

Throughout Japanese art metal work, in which I hope you will take increasing interest, there is the one principle of extreme simplicity and absolute fidelity to nature. The brilliant metals, gold and silver, are used most sparingly, only for enrichment, and to heighten the general effect; these precious metals are never allowed to assert themselves unduly, and are only employed where their presence will serve some definite end in relation to the design as a whole. A Japanese proverb asserts that "He who works in gold puts his brains into the melting pot," meaning, I suppose, that this metal, so precious from an artistic point of view, demands for its successful application the utmost effort of the workman, and suggesting that gold should not be employed in massive forms such as would result from melting and casting, but should be daintily handled, beaten on to the work, or embedded with the hammer.

Bear in mind that in Birmingham, when a really fine work is produced in silver, the surface is often made gray by chemical means, "oxidised," as it is termed, and this subordination of the brilliancy of silver to artistic effect is well understood by the celebrated American firm, Messrs. Tiffany, of New York, who are doing so much to catch the spirit of Japanese art metal work. All I ask you to do is to carry this still further—to cover base metals with these glowing coloured oxides, and thus to add to the permanence of art work, by producing surfaces which will resist the unfavourable atmospheric influences of our cities.

Hitherto we have considered the union of metals by fusion, but fire is not the only agent which can be employed for this purpose. Two or more metals may be deposited side by side by the aid of the electric battery. Birmingham was, as you well know, the early home of electro-metallurgy, an industry to the development of which the great firm of Elkington has so materially contributed. I have no statistics as to the amount of precious metals annually employed for electro-deposition in Birmingham, but it is known that a single works in Paris, belonging to M. Christofle, deposits annually 6 tons of silver, and it has been estimated that the layer of silver of the thickness actually deposited on various articles would, if spread out continuously, cover an area of 140 acres.[1] I will not, however, dwell upon the deposition of gold and silver in their normal colours. I would remind you that copper and zinc may be deposited by electrolysis so as to form brass, and that all the beautiful bronzes and alloys of the Japanese can be obtained by galvanic agency; and further, by suitable admixtures of gold, silver, and copper, red-gold, rose-coloured gold, or green gold may be deposited, so that the electro-metallurgist has at his command the varied palette of the decorative artist.

[The images of deposits of coloured gold, specially prepared by Messrs. Elkington, were then projected on the screen.]

I ought to allude to what has been called the moral aspect of colour, and although I cannot follow Goethe[2] in his attributes of colour, which seem to me to be fantastic and over-strained, I quite recognise the poetic sympathy

[1] H. Bouilhet, *Ann. de Chim. et de Phys.*, t. xxiv., p. 549, 1881.
[2] Farbenlehrer.

of Shakespeare in making Bassanio select the casket of lead, which contained the warrant for his earthly happiness, because "its paleness moved him more than eloquence." I ask you to remember Ruskin's words, that "all men completely organised and justly tempered enjoy colour; it is meant for the perpetual comfort and delight of the human heart; it is richly bestowed on the highest works of creation, and the eminent sign and seal of perfection in them being associated with life in the human body, with light in the sky, with purity and hardness in the earth; death, night, and pollution of all kinds being colourless."

BIBLIOGRAPHY OF LECTURES ON ALLOYS AND ART METAL WORK.

CANTOR LECTURES TO THE ROYAL SOCIETY OF ARTS.

First Series, 1884.

Alloys used for Coinage. Four Lectures. (*Journ. Soc. Arts*, vol. xxxii., pp. 804, 835, 881, and 911.) (See portion dealing with Mint work, pp. 29-66.)

Second Series, 1888.

Alloys. Three Lectures. (*Journ. Soc. Arts*, vol. xxxvi., pp. 1111, 1125, and 1137.)

I. Sketch of early investigations on Alloys.—Development of views as to their constitution from the time of Réaumur (1722) to that of Matthiessen (1860).—Recent investigations.—Formation of Alloys by Fusion.—Results obtained by compr ssing the finely divided Constituent Metals.—Evolution and absorption of Heat attending the union of Metals.—Production of Ice by the aid of Amalgamation.—Debray's explosive Alloys.

II. Influence of varying quantities of Metals on each other.—Exceptional effects of "traces" of impurity.—Certain physical constants of Alloys.—Evidence as to allotropic states of their constituent Metals.

III. Colours of Metals and of Alloys considered in relation to their application to art, with illustrations mainly taken from Oriental art metal work.

Third Series, 1893.

Alloys. Four Lectures. (*Journ. Soc. Arts*, vol. xli., pp. 977, 993, 1006, and 1022.)

I. and II. Analogy of Alloys and Solutions.—Importance of studying the behaviour of Alloys as they liquefy and as they "freeze."—Experimental methods adopted in conducting the investigations.

III. Advances in knowledge of Alloys since the last course of Cantor Lectures in 1888.

IV. Applications of Alloys to metal work, with special reference to the art collections in the South Kensington Museum.

Fourth Series, 1897.

Alloys. Four Lectures. (*Journ. Soc. of Arts*, vol. xlv., pp. 1151, 1163, and 1176.)

I. Alloys which are solutions of the constituent Metals and those which contain chemical compounds.

II. and III. The diffusion of liquid and solid Metals.—Steel and Cast Iron considered as Carbon-iron Alloys.

IV. Advances in knowledge of Alloys since the last course of Cantor Lectures in 1893.

The Colours of Metals and Alloys. British Association Lecture, 1886.—*Nature*, xxxv., Dec. 2, 1886 (see pp. 361-371 of this volume).

The Use of Alloys in Art Metal Work. Lecture to the Applied Art Section of the Royal Society of Arts.—(*Journ. Soc. Arts*, June 13, 1890.)

Analysis of Oriental Metal Work at South Kensington (carried out by the late Arthur Wingham), 1892.

Bronze and the London Atmosphere. Lecture at South Kensington, 1891.—*Nature*, xlv., p. 443.

Mural Painting by the aid of Soluble Silicates and Metallic Oxides (in collaboration with Mrs. Lea Merritt), 1895.—*Journ. Soc. Arts*, Dec. 6, 1895.

Japanese Metal Work.—*16th Mint Report*, 1885.

Bronze for Casting Medals.—*16th Mint Report*, 1885.

Treatment of the Surfaces of Medals.—*28th Mint Report*, 1897, and *Nature*, lviii., p. 236.

Alloys for Bronze Medals.—1901, *31st Mint Report*, and *Nature*, lxiv., p. 309.

IX.

GENERAL BIBLIOGRAPHY OF ROBERTS-AUSTEN'S WORK.

1868. On the Occurrence of Organic Appearances in Colloid Silica obtained by Dialysis.—*Chem. Soc. Journ.*, vi., 1868, pp. 274-276; *Chem. News*, 1868, pp. 175 and 195.

1869. Note on the Experimental Illustration of the Expansion of Palladium attending the Formation of its Alloy with Hydrogenium.—*Phil. Mag.*, xxxviii., 1869, pp. 51-53; *Annales de Chimie*, xviii., 1869, pp. 381-384; *Student*, iii., 1869, pp. 311-312.

Notes on Stalactites.—*Nature*, i.

1870. On the Absorption of Hydrogen by Electro-deposited Iron.—*Brit. Assoc. Report*, xl., 1870 (sect.), p. 62.

1871. The Molecular Arrangement of the Alloy of Silver and Copper employed for the British Silver Coinage.—*Brit. Assoc. Report*, xli., 1871 (sect.), p. 80.

1873. Report of the Committee appointed for the purpose of inquiring into the method of making Gold Assays.—*Brit. Assoc. Report*, xliii., 1873, pp. 219-222; *Chem. News*, Oct. 3, p. 174.

1874. On the Preparation of Standard Trial Plates to be used in verifying the composition of the Coinage.—*Chem. Soc. Journ.*, xii., 1874, pp. 197-203; *Chem. News*, Dec. 26, 1873, p. 323.

On the Columnar Form of Basalt.—*Brit. Assoc. Report*, 1874 (sect.), pp. 91-92.

1875. On the Liquation, Fusibility, and Density of certain Alloys of Silver and Copper.—*Roy. Soc. Proc.*, clxii., 1875, pp. 481-495; *Chem. News*, xxxi., 1875, p. 143; *Annales de Chimie*, xiii., 1878, pp. 111-132.

Second Report of the Committee appointed for the purpose of inquiring into the method of making Gold Assays and of stating the Results thereof.—*Brit. Assoc. Report*, 1875, pp. 155-156; *Nature*, xii.

On the Electro-deposition of Iron.—*Chem. News*, Mar. 25, p. 137.

1876. On the Apparatus employed by the late Mr. Graham, F.R.S., in his Researches.—*Nature*, xiv., 1876, pp. 511-514.

1877. On the Artificial Production of Columnar Structure.—*Chem. News*, Jan. 26.

Alloy of Platinum and Iridium for a New Standard of Length.—*Nature*, xv., p. 336.

1878 Alliages d'or et de cuivre (trad.).—*Annales de Chimie*, xiii., 1878, pp. 133-140.

On the Detection of Sounds which accompany the Diffusion of Gases through a Thin Septum.—*Brit. Assoc.*, Dublin, 1878.

1879. The "Graham Lecture" of the Philosophical Society of Glasgow. [Graham's Researches on Molecular Movement.]—*Glasgow Phil. Soc. Proc.*, ii., 1879, pp. 345-364; *Nature*, xix., p. 291.

Some Experiments with the Voltaic Induction Balance.—*Brit. Assoc. Report*, 1879, p. 303.

Note on the Examination of certain Alloys by the aid of the Induction Balance.—*London Phys. Soc. Proc.*, iii., 1880, pp. 89-93; *Phil. Mag.*, viii., 1879, pp. 57-60.

On an Analogy between the Conductivity for Heat and the Induction Balance Effect of Copper-Tin Alloys. [1879.]—*London Phys. Soc. Proc.*, iii., 1880, pp. 156-158; *Phil. Mag.*, viii., 1879, pp. 551-553.

Some Experiments with the Voltaic Induction Balance.—*Brit. Assoc.*, Sheffield, 1879.

1880. Copper-Tin Alloys.—*Nature*, xxi., p. 272.

Flashing of Cupelled Buttons.—*Nature*, xxi., p. 531; and *Chem. News*, March 19 and June 11, 1880.

Introductory Lecture to the Course of Metallurgy at the Royal School of Mines, Session 1880-81.—*Chem. News*, xlii., 1880, pp. 254-257, 263-267; *Nature*, xxiii., 1881, pp. 65-69.

1881. Steel for the Manufacture of Dies.—*Chemical News*, xliii., 1881, pp. 239-241; also *Appendix to the Eleventh Mint Report*.
Results of Experiments made with a view to ascertain whether Occluded Gases play any part in the Hardening and Tempering of Steel.—*Instit. Mech. Eng. Proc.*, 1881, pp. 706-711; *Chem. News*, Jan. 17, 1881.
1883. On some Theoretical Considerations connected with the Hardening and Tempering of Steel.—*Chem. News*, xlvii., 1883, p. 195; *Nature*, xxvii., 1883.
On the Mobility of Gold and Silver in Molten Lead.—*Brit. Assoc.*, 1883.
1884. Alloys used for Coinage. Cantor Lectures.—*Journ. Roy. Soc. of Arts*, vol. xxxii., pp. 804, 835, 881, and 911; also *Chem. News*, pp. 131 and 188.
1885. Development of Technical Instruction in Metallurgy.—*Chem. News*, Oct. 9, 1885.
1886. Certain Properties common to Fluids and Solid Metals. Royal Institution Lecture.—*Proc. Roy. Inst.*, vol. xi., p. 395.
The Colours of Metals and Alloys. Brit. Assoc. Lecture.—*Nature*, xxxv., Dec. 2, 1886.
1887. The Electro-deposition of Iron.—*Journ. Iron and Steel Inst.*, 1887, No. 1.
Experiments on the possible Electrolytic Decomposition of Alloys. (*Brit. Assoc. Report.*)—*Nature*, xxxvi., p. 547.
1888. On certain Mechanical Properties of Metals considered in relation to the Periodic Law.—*Phil. Trans. Roy. Soc.*, clxxix., pp. 339-349; *Proc. Roy. Soc.*, xliii., pp. 425-428; *Nature*, xxxvii., p. 497, and xli., p. 420.
The Impossibility of Electrical Separation of the Constituents of Alloys.—*Nature*, xxxvii., p. 303.
Some Curious Properties of Metals and Alloys. Royal Institution Lecture.—*Proc. Roy. Inst.*, vol. xii., p. 267; *Nature*, xxxix., p. 83.
Alloys. Cantor Lectures.—*Journ. Roy. Soc. of Arts*, vol. xxxvi., 1111, 1125, and 1137.
1889. Tribute to Dr. John Percy.—*Nature*, xl., p. 206.
On the Hardening and Tempering of Steel. (Address to the Brit. Assoc.)—*Nature*, xli., pp. 11, 32.
1890. The Use of Alloys in Art Metal Work. (Lecture to the Applied Art Section of the Royal Society of Arts.)—*Journ. Soc. Arts*, June 13, 1890.
Carburisation of Iron by the Diamond.—*Journ. Iron and Steel Inst.*, 1890, No. 1; *Nature*, xlii., p. 69.
1891. The Introduction to the Study of Metallurgy. (Publication of the First Edition.)—Reviewed by *Nature*, xliii., p. 530; *Chem. News*, Feb. 6, 1891.
The First Report of the Alloys Research Committee of the Institute of Mechanical Engineers.—*Proceedings*, 1891, p. 543; *Nature*, xlv., p. 22.
Address to the Chemical Section of the British Association (Cardiff Meeting).—*Nature*, xliv., p. 399; *Chem. News*, pp. 103 and 115.
Bronze and the London Atmosphere. Lecture at South Kensington.—*Nature*, xlv., p. 443.
On certain Properties of Metals considered in Relation to the Periodic Law.—*Proc. Roy. Soc.*, xlix., pp. 347-356.
Automatic Methods of Observation in the use of the Le Chatelier Pyrometer.—*Journ. Iron and Steel Inst.*, 1891, No. 1.
1892. Metals at High Temperatures. Royal Institution Lecture.—*Proc. Roy. Inst.*, vol. xii., p. 502; *Nature*, xlv., p. 534.
On the Melting Points of the Gold-Aluminium Series of Alloys.—*Proc. Roy. Soc.*, l., pp. 367-368.
The "Purple" Alloy of Gold and Aluminium.—*Nature*, xliv., p. 111.
On an Appliance for Autographically Recording the Temperatures of Furnaces.—*Journ. Iron and Steel Inst.*, 1892, No. 2; *Nature*, xlvi., p. 526.
On the Measurement of High Temperatures.—*Proc. Inst. Civil Eng.*, May, 1892.
Analysis of Oriental Metal Work at South Kensington (carried out by the late Arthur Wingham).
1893. The Second Alloys Research Report.—*Proc. Inst. Mech. Eng.*, 1893, p. 102; *Nature*, xlvii., p. 617; *Chem. News*, 1893, p. 318.
Alloys. Cantor Lectures.—*Journ. Roy. Soc. of Arts*, vol. xli., pp. 977, 993, 1006, and 1022.
The Recording Pyrometer.—*Journ. Iron and Steel Inst.*, 1893, No. 1; *Nature*, xlviii., p. 113.
Recent Advances in Pyrometry.—*Trans. Amer. Inst. Min. Eng.*, Aug. 1893.

1894. The Introduction to the Study of Metallurgy. Second Edition.—Reviewed in *Nature*, l., p. 147; *Chem. News*, 1894, p. 159.
Electrolysis of Glass. (British Association Meeting.)—*Nature*, l., p. 410.
1895. The Third Alloys Research Report.—*Proc. Inst. Mech. Eng.*, 1895, p. 238; *Nature*, lii., p. 18.
The Rarer Metals and their Alloys. Royal Institution Lecture.—*Proc. Roy. Inst.*, vol. xiv., p. 497; *Nature*, lii., pp. 14, 39.
The Electric Furnace. (Roy. Soc. Conversazione.)—*Nature*, lii., p. 37.
Micrographic Analysis.—*Nature*, lii., p. 367.
1896. The Diffusion of Metals. (Bakerian Lecture to the Royal Society.)—*Phil. Trans. Roy. Soc.*, clxxxvii., pp. 383-415; *Proc. Roy. Soc.*, lix., pp. 281-285; *Nature*, liv., p. 55.
The Structure of Metals—Its Origin and Changes. [In collaboration with F. Osmond.]—*Phil. Trans. Roy. Soc.*, clxxxvii., pp. 417-432.
The Electrical Heating of Aluminium Wire. (Roy. Soc. Conversazione.)—*Nature*, liv., p. 37.
The Diffusion of Carbon in Iron.—*Journ. Iron and Steel Inst.*, 1896, No. 1.
1897. The Fourth Alloys Research Report.—*Proc. Inst. Mech. Eng.*, 1897, p. 31. *Nature*, lv., p. 377.
A Recording Pyrometer for Industrial Use.—*Journ. Soc. Chem. Ind.*, Jan., 1897.
Canada's Metals. British Assoc. Lecture.—*Nature*, lvi., p. 463, and lvii., p. 533.
Alloys. Cantor Lectures.—*Journ. Roy. Soc. of Arts*, vol. xlv., pp. 1151, 1163, and 1176.
1898. Surfusion in Metals and Alloys.—*Proc. Roy. Soc.*, lxiii., pp. 447-454; *Nature*, lviii., p. 619.
Extraction of Nickel from its Ores by the Mond Process.—*Proc. Inst. Civil Eng.*, vol. cxxxv., 1898-99, part 1; *Chem. News*, 1898, p. 260; *Nature*, lix., p. 63.
Treatment of the Surfaces of Metals. [*28th Mint Report*, 1897.]—*Nature*, lviii., p. 236.
Action of Projectiles and the Explosives on Tubes of Steel Guns.—*Journ. Iron and Steel Inst.*, 1898, No. 2; *Brit. Assoc. Report, Toronto*, 1897; *The Times*, Aug. 23, 1897.
1899. The Fifth Alloys Research Report.—*Proc. Inst. Mech. Eng.*, 1899, p. 35; *Nature*, lix., p. 566.
Presidential Address to the Iron and Steel Institute.—*Journ. Iron and Steel Inst.*, 1899, No. 1; *Chem. News*, 1899, pp. 246, 257, and 271.
Photomicrography of Steel Rails.—*Proc. Inst. Civil Eng.*, 1899, pp. 36-38.
The Nature of Fracture of Armour Plates.—*Fielden's Magazine*, August, 1899.
1900. The Diffusion of Gold in Solid Lead at Ordinary Temperatures.—*Proc. Roy. Soc.*, lxvii., pp. 101-105.
Presidential Address to the Iron and Steel Institute.—*Journ. Iron and Steel Inst.*, 1900, No. 2.
Report on the Wear of Steel Rails to the Board of Trade.—H.M. Stationery Office, 1900.
Molecular Unrest in Solids.—*Proc. Phil. Soc. of Glasgow*, April, 1900.
1901. Metals as Fuel. Royal Institution Lecture.—*Prac. Roy. Inst.*, vol. xvi., p. 496; *Nature*, lxiv., p. 360.
Alloys for Bronze Metals. 31st Mint Report.—*Nature*, lxiv., p. 309.
1902. Metallurgy in its Relations to Engineering. (James Forrest Lecture to the Inst. of Civil Engineers.)—*Proc. Inst. Civil Eng.*, xix., p. 218; and *Nature*, lxvi., p. 18.

Papers in Collaboration with Others.

Roberts and Lockyer.
(1) On the Quantitative Analysis of certain Alloys by means of the Spectroscope.—*Roy. Soc. Proc.*, xxi., 1873, pp. 507-508; *Phil. Trans.*, clxiv., 1874, pp. 495-499.
Roberts and Slack.
On Fungoid Growths in Aqueous Solutions of Silica and their Artificial Fossilisation.—*Micro. Soc. Trans.*, xvi., 1868, pp. 105-108.

Roberts and Wright.

On the Condition of the Hydrogen occluded by Palladium as indicated by the Specific Heat of the Charged Metal.—*Chem. Soc. Journ.*, xi., 1873, pp. 112-123.

Roberts-Austen and Lockyer.

(2) On the Absorption Spectra of Metals volatilised by the Oxy-hydrogen Flame.—*Roy. Soc. Proc.*, xxiii., 1875, pp. 344-349; *Phil. Mag.*, i., 1876, pp. 234-239.

Roberts-Austen and Wrightson.

(1) On the Density of Fluid Bismuth.—*Brit. Assoc. Report*, 1880, pp. 543-544; *London Phys. Soc. Proc*, iv., 1881, pp. 195-199; *Phil. Mag.*, xi., 1881, pp. 295-299.

(2) On the Fluid Density of certain Metals. (1882.)—*London Phys. Soc. Proc.*, v., 1884, pp. 97-104; *Phil. Mag.*, xiii., 1882, pp. 360-367; *Annales de Chimie*, xxx., 1883, pp. 274-288.

Roberts-Austen, Luff and Wright.

Report on the Chemistry of some of the lesser-known Alkaloids, especially Veratria and Bebierine.—*Brit. Assoc. Report*, pp. 1878, 105-107.

Roberts-Austen and F. Osmond.

The Structure of Metals—Its Origin and Changes.—*Phil. Trans. Roy. Soc.*, clxxxvii., pp. 417-432.

Roberts-Austen and T.-K. Rose.

On certain Properties of the Alloys of the Gold-Copper Series.—*Proc. Roy. Soc.*, lxvii., pp. 105-112; *Nature*, lxii. p. 93; *Chem. News*, 1900, p. 241.

On certain Properties of the Alloys of the Gold-Silver Series.—*Proc. Roy. Soc.*, lxxi., pp. 161-163; *Nature*, lxvii., p. 285.

Roberts-Austen and A. Stansfield.

The Constitution of the Metallic Alloys—Report presented to the International Congress of Physics at Paris, 1900. See also Appendix to the Sixth Report of the Alloys Research Committee (*Proc. Inst. Mech. Eng.*, 1904).

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